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ACADEMIC DISSERTATION
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Responsible supervisor and Custos	Prof. Sami Pajunen Tampere University Finland	
Supervisors	D.Sc. Valtteri Hongisto Turku University of Applied Sciences Finland	Prof. Juha Vinha Tampere University Finland
Pre-examiners	Prof. Jin Yong Jeon Hanyang University Republic of Korea	Ph.D. Catherine Guigou-Carter Centre Scientifique et Technique du Bâtiment France
Opponent	Ph.D. Pyoung-Jik Lee University of Liverpool United Kingdom	

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PREFACE

The process from my first ideas concerning a study on impact sound insulation to the publication of this dissertation has taken more than 20 years. It was probably in 1997 when I realized that the single-number quantities for impact sound insulation do not work correctly and why it is so. I also understood that a wide scale of floors should be measured using both tapping machine and walking as a sound source. This kind of study, however, did not became possible earlier than in 2012.

Many people have affected my research work during the years. First, I would like to express my gratitude to Prof. Ralf Lindberg, who appointed me as a research assistant in 1995 to work in a project concerning sound insulation of wooden apartment buildings. Later, he has supported my career in many ways, also as the first responsible supervisor of my dissertation until his retirement. The researcher responsible for the sound insulation project in 1995 was forever energetic Mr Asko Keronen, with whom I started to study acoustics.

This dissertation is mainly based on the materials produced during the research project "User-oriented development of sound insulation in buildings ÄKK" (2012–2014). The ÄKK project was lead by Dr Valtteri Hongisto, who has also been the second supervisor of my dissertation. I am grateful for having the possibility to work with him and for many instructive discussions about building acoustics and research. During the last years, Prof. Sami Pajunen has been the responsible supervisor of my dissertation providing his support, which I appreciate very much.

My deepest thanks are directed to my former research assistants and current colleagues Mr Ville Kovalainen, Mr Jesse Lietzén and Mr Joose Takala. Without their help and enthusiasm this work would not have been possible. I am also very grateful to my co-authors, Ms Petra Virjonen for her work in conducting the optimization process for derivation of the new single-number quantities and Mr David Oliva for the realisation of the psychoacoustical experiment. Furthermore, I would like to thank Dr Jukka Lahdensivu for many interesting and lively discussions about science, which have given inspiration to reporting the research results and writing the publications.

The pre-examiners of my dissertation have been Prof. Jin Yong Jeon and Dr Catherine Guigou-Carter. I would like to thank them for their efforts in pre-examining my work. Their supportive feedback and valuable comments have encouraged me to carry on.

The ÄKK project was funded by Tekes – the Funding Agency for Technology and Innovation, Ministry of Environment and eight companies of building industry. Thanks are due to the steering group of the project and especially its chairman Mr Ari Saarinen. I wish to acknowledge also the support granted by the Finnish Foundation for Technology Promotion for the preparation of this thesis.

Tampere, 2nd of June 2019

Mikko Kylliäinen

ABSTRACT

Impact sounds are different living sounds directed at floors in dwellings. Objective single-number quantities used in rating the impact sound insulation of floors and between dwellings have been presented in standard ISO 717-2 (2013). It has long been recognised that the standardised single-number quantities do not correlate well with the subjective judgement of living impact sounds. The main objective of this thesis was to develop new single-number quantities that would correspond better with the subjective experience of living impact sounds transmitted from the neighbouring dwelling upstairs.

New single-number quantities concern five different living impact sounds. In addition, the purpose was to develop a single-number quantity that explains the annoyance caused by all five impact living sounds. Experimental data for the development of the new single-number quantities was produced by measuring the impact sound insulation of concrete floors with a wide scale of floor coverings. Five spectrally different living impact sounds were also measured and recorded. These sounds were walking with socks, hard and soft shoes, super ball bouncing and chair moving. A psychoacoustic experiment with an extensive number of participants was conducted to find out the loudness and annoyance of the living impact sounds and, furthermore, the associations between the subjective judgement of the sounds and objective single-number quantities. The experimental data of the impact sound insulation measurements and the psychoacoustic experiment was utilised in mathematical optimisation of new single-number quantities.

As a starting point for the formulation of the new single-number quantities, it was required for them to be able to be expressed as the sum of the present single-number quantity $L'_{n,w}$ or $L'_{nT,w}$ and a new spectrum adaptation term instead of C_I or $C_{I,50\text{-}2500}$. An optimised reference spectrum could be developed for each of the five sound types, each leading to a better correlation between the subjective judgement of the annoyance of the sounds and the single-number quantities than can be achieved by using any of the single-number quantities presented in the standard ISO 717-2. In addition, an optimised reference spectrum was derived which explained the annoyance of all five sound types reasonably well (coefficient of determination

$R^2 = 0.93$) and better than any of the standardised single number quantities (e.g. $R^2 = 0.86$ for $L'_{n,w} + C_{I,50-2500}$).

Another objective of the thesis was to study the measurement uncertainties of various single-number quantities for rating the impact sound insulation at a frequency range of 50 Hz and above. It was shown that the measurement uncertainty of a single-number quantity depends on the impact sound spectrum of the floor type. The results also indicate that the uncertainty depends on the extent that the single-number quantity weights the low frequencies. The measurement uncertainty at a low frequency range, however, does not become so large that it would prevent developing new reference curves that weight this frequency range more strictly than the present, standardised reference curves starting at 100 Hz.

TIIVISTELMÄ

Askeläänet ovat erilaisia asumisesta syntyviä lattiaan kohdistuvia ääniä. Objektiivisia teknisiä mittalukuja välipohjarakenteiden ja asuntojen välisen askeläänieristävyyden arvioimiseksi on esitetty standardissa ISO 717-2 (2013). Jo pitkään on tiedetty, että standardoidut mittaluvut eivät korreloi hyvin askeläänieristävyyden subjektiivisten arvioiden kanssa. Tämän tutkimuksen päätavoite oli kehittää uusia mittalukuja, jotka vastaisivat paremmin subjektiivista kokemusta askeläänistä, jotka välittyvät ylhäältä naapurihuoneistoista alas.

Uudet mittaluvut perustuvat viiteen erilaiseen asumisen aiheuttamaan askeläänieen. Tavoitteena oli kehittää myös yksi mittaluku, joka vastaisi mahdollisimman hyvin kaikkien viiden askeläänen aiheuttamaa häiritsevyyttä. Kokeellinen aineisto uusien mittalukujen kehittämiseksi tuotettiin mittaamalla eri tavoin päällystettyjen betonivälipohjien askeläänieristävyyttä sekä äänittämällä ja mittaamalla viiden erilaisen asumisessa esiintyvän askeläänen synnyttämät äänispektrit. Nämä viisi asumisessa esiintyvää askelääntä olivat kävely sukin, kovapohjaisin ja pehmeäpohjaisin kengin, superpallon pompottelu sekä tuolin siirto lattialla. Äänitettyjen askeläänten häiritsevyyttä ja äänekkyyttä tutkittiin psykoakustisella kokeella, johon osallistui suuri määrä koehenkilöitä. Sen tulosten yhteyksiä askeläänieristävyyden mittalukuihin tutkittiin ja kokeilla tuotettua aineistoa käytettiin matemaattiseen optimointiin, jonka avulla johdettiin uusia mittalukuja askeläänieristävyyden arvioimiseen.

Lähtökohtana uuden mittaluvun muodostamiselle oli, että se oli pystyttävä ilmaisemaan pitkään käytettyjen askeläänitasolukujen $L'_{n,w}$ ja $L'_{nT,w}$ sekä johdettavan uuden spektripainotustermin summana nykyisin käytettävien spektripainotustermien C_I ja $C_{I,50\text{-}2500}$ sijasta. Jokaiselle viidestä tutkitusta askeläänestä saatiin johdetuksi optimoitu referenssispektri, ja näin aikaansaadut mittaluvut korreloivat subjektiivisesti askeläänistä koetun häiritsevyyden kanssa paremmin kuin yksikään standardissa ISO 717-2 esitetty mittaluku. Lisäksi johdettiin optimoitu referenssispektri ja mittaluku, joka vastaa kaikista viidestä askeläänestä koettua häiritsevyyttä varsin hyvin (selitysaste $R^2 = 0{,}93$) ja paremmin kuin mikään standardoiduista mittaluvuista (esim. askeläänitasoluvulle $L'_{n,w} + C_{I,50\text{-}2500}$ on $R^2 = 0{,}86$).

Tutkimuksen toinen tavoite oli selvittää erilaisten askeläänieristävyyden mittalukujen mittausepävarmuutta, kun askeläänieristävyyttä arvioidaan 50 Hz keski-

taajuudella ja ylemmillä taajuuskaistoilla. Mittalukujen mittausepävarmuuden voitiin osoittaa riippuvan mitatun välipohjarakenteen tuottamasta askeläänispektristä ja siitä, kuinka paljon kukin mittaluku painottaa pieniä taajuuksia. Mittausepävarmuus pienillä taajuuksilla ei kuitenkaan ole niin suuri, että se muodostuisi esteeksi uusien, pieniä taajuuksia nykyisiä mittalukuja enemmän painottavien mittalukujen kehittämiselle.

CONTENTS

ABBREVIATIONS

A	Absorption area [m^2]
A_0	Reference absorption area [m^2]
C_I	Spectrum adaptation term defined at frequency range 100–2500 Hz [dB]
$C_{I,50\text{-}2500}$	Spectrum adaptation term defined at frequency range 50–2500 Hz [dB]
D	Deviation [dB]
$L_{A,eq}$	Equivalent A-weighted sound pressure level [dB]
$L_{A,F,max}$	Maximum A-weighted sound pressure level with time weighting FAST [dB]
$L_{F,max}$	Maximum sound pressure level with time weighting FAST [dB]
$L_{impact,j}$	Impact source power level of the tapping machine for frequency band j [dB]
L_j	Level of reference spectrum at frequency band j [dB]
L_n	Normalised impact sound pressure level measured in a laboratory [dB]
$L'_{n,Bod}$	Weighted normalised impact sound pressure level according to Bodlund (1985) [dB]
$L'_{n,Fas,50}$	Weighted normalised impact sound pressure level according to Fasold (1965) at frequency range 50–3150 Hz [dB]
$L'_{n,Fas,100}$	Weighted normalised impact sound pressure level according to Fasold (1965) at frequency range 100–3150 Hz [dB]
$L'_{n,Ger}$	Weighted normalised impact sound pressure level according to Gerretsen (1976) [dB]
$L_{n,Hag}$	Weighted normalised impact sound pressure level according to Hagberg (2010) [dB]
$L_{n,w}$	Weighted normalised impact sound pressure level measured in a laboratory [dB]
L'_n	Normalised impact sound pressure level measured in a building [dB]

$L'_{\mathrm{n,w}}$	Weighted normalised impact sound pressure level measured in a building [dB]
$L'_{\mathrm{n}T}$	Standardised impact sound pressure level in a building [dB]
$L'_{\mathrm{n}T,\mathrm{w}}$	Weighted standardised impact sound pressure level in a building [dB]
L_{N}	Loudness level [phon]
NR	Noise rating
p	Probability value
R	Pearson’s correlation coefficient
R^2	Coefficient of determination
R_{i}	Impact sound reduction index [dB]
R_{impact}	Weighted impact sound reduction index [dB]
s'	Dynamic stiffness [MN/m3]
SNQ	Single-number quantity
SPL	Sound pressure level
t	Time [s]
T	Reverberation time [s]
V	Volume [m^3]
ΔL_{w}	Weighted reduction in the impact sound pressure level [dB]

ORIGINAL PUBLICATIONS

Publication I	Kylliäinen, M., Lietzén, J., Kovalainen, V. & Hongisto, V. 2015. Correlation between single number-quantities of impact sound insulation and noise ratings of walking on concrete floors. *Acta Acustica united with Acustica* **101**(5), 975–985.
Publication II	Kylliäinen, M., Hongisto, V., Oliva, D. & Rekola, L. 2017. Subjective and objective rating of impact sound insulation of a concrete floor with various coverings. *Acta Acustica united with Acustica* **103**(2), 236–251.
Publication III	Kylliäinen, M., Virjonen, P. & Hongisto, V. 2019. Optimized reference spectrum for rating the impact sound insulation of concrete floors. *The Journal of the Acoustical Society of America* **145**(1), 407–416.
Publication IV	Kylliäinen, M. 2014. The measurement uncertainty of single-number quantities for rating the impact sound insulation of concrete floors. *Acta Acustica united with Acustica* **100**(4), 640–648.
Publication V	Kylliäinen, M., Kovalainen, V., Lietzén, J. & Hongisto, V. 2014. Uncertainty of alternative single-number quantities for rating of impact sound insulation. *Proceedings of Forum Acusticum 2014*. Krakow, September 7–12, paper SS01-5.

1 INTRODUCTION

1.1 Standardised rating method of impact sound insulation

Impact sounds are different living sounds directed at floors, especially in dwellings. Examples of sources of the impact sounds are walking on the floor, falling objects, moving furniture and children playing. Impact sounds from neighbouring dwellings are among the living sounds that may cause annoyance (Langdon *et al.* 1993). Annoyance defined in standard ISO 15666 (2003) is considered as a predecessor of more serious health effects.

Because of the possible health effects resulting from the annoyance provoked by the impact sounds, many countries have set regulatory limits for impact sound insulation between dwellings (Rasmussen & Rindel 2010). The impact sound insulation at a certain frequency is expressed as normalised impact sound pressure level L'_{n} or standardised impact sound pressure level $L'_{\mathrm{n}T}$ (ISO 16283-2, 2015) measured in a room when a sound source, tapping machine, is operating in a neighbouring dwelling. Therefore, the measurement result is better the lower the impact sound pressure level is.

The impact sound insulation of floors and between dwellings is dependent on frequency and, therefore, the measurements of impact sound pressure levels (SPL) are carried out at 1/3-octave centre frequency bands at a wide frequency range. Presenting the measurement results at frequency bands is an exact way to express the impact sound insulation. For practical reasons, the allowable values for impact sound insulation are given as single-number quantities (SNQ), either as weighted normalised impact SPL $L'_{\mathrm{n,w}}$ or weighted standardised impact SPL $L'_{\mathrm{n}T\mathrm{,w}}$ (ISO 717-2, 2013; ISO 16283-2, 2015). These SNQs are determined from measurement results at frequency bands from 100 Hz to 3150 Hz (**Figure 1**).

The revision of the ISO standard 717-2 in 1996 introduced spectrum adaptation terms, of which the term $C_{\mathrm{I,50\text{-}2500}}$ made it possible to enlarge the measured frequency range down to 50 Hz. Several countries have adopted this term into use and a sum $L'_{\mathrm{n,w}} + C_{\mathrm{I,50\text{-}2500}}$ or $L'_{\mathrm{n}T\mathrm{,w}} + C_{\mathrm{I,50\text{-}2500}}$ as a limiting value in their national building regulation (Rasmussen & Machimbarrena 2014).

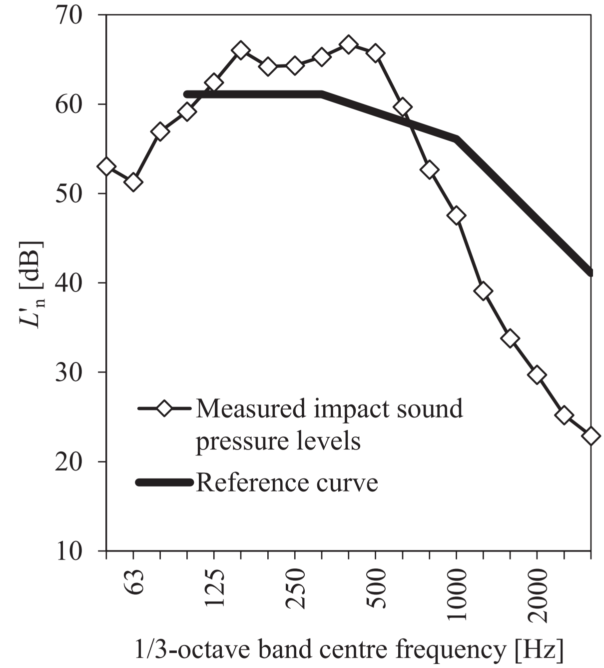

Figure 1. An example of an impact sound insulation measurement. The dark continuous line is the reference curve and the dots show the measurement results. The single-number quantity, in this case weighted normalised impact SPL $L'_{n,w}$, is read from the reference curve at 500 Hz when the curve is in such a position that the unfavourable deviations between the measurement results and the reference curve values do not exceed 32 dB. The value of $L'_{n,w}$ is 59 dB.

The purpose of the SNQs is to describe the impact sound insulation of floors and between dwellings in a way that connects the physical properties and measurement results with the occupants' perceived annoyance of the living impact sounds heard from neighbouring dwellings. It has long been recognised that the SNQs presented in the standard ISO 717-2 (2013) and its earlier versions do not correlate especially well with the subjective judgement of living impact sound sources directed at different floors (e.g. Mariner 1963; Watters 1965; Fasold 1965; Mariner & Hehmann 1967; Olynyk & Northwood 1968; Gerretsen 1976; Bodlund 1985; Hagberg 2010).

1.2 Development of the standardised rating method

The present method to express the impact sound insulation is a result of a long development process. The equipment for reliable and repeatable acoustical measurements was developed during the First World War. Laboratory testing of different acoustic properties of building materials and structures started rapidly after the war. Sound insulation of dwellings also became a question of interest by the 1930s (Thompson 2002; Kylliäinen 2009). This was affected by an increasing number of cars and traffic noise and the appearance of new domestic sound sources like radio and gramophone (Thompson 2002; Bijsterveld 2008). Sound insulation between dwellings also changed when traditional floor constructions were replaced by thin monolithic concrete slabs which were effective as load bearing structures but not massive enough for sufficient sound insulation (Bijsterveld 2008).

Before the middle of the 1930s, impact sound insulation was evaluated by subjective methods. For example, a steel ball was dropped on the floor from different heights and the sound generated in this way was listened to by the test participants. An indicator for impact sound insulation was the height from which the sound of the falling ball could not be heard by the participants (Hofbauer 1935; Osswald 1936). The subjective methods resulted in the ranking of different floor structures, but they did not give any information regarding the reasons for that, such as the physical or acoustic performance of the structures. Therefore, researchers found a need for an objective sound source and evaluation method. Until the end of the decade, a tapping machine was used widely in many countries, e.g. England, the United States and Germany (Chrisler 1930; Reiher 1932; Chrisler & Snyder 1934; Hofbauer 1935; Kaye 1936; Lindahl & Sabine 1940).

The standardisation of an objective impact sound source was first suggested in Germany in 1936 (Gastell 1936). The properties of the suggested tapping machine were defined mainly in a similar way as today: five steel hammers having a mass of 500 g fall from a height of 40 mm twice a second each. The present standards ISO 10140-3 and 10140-5 (2010) for laboratory measurements and ISO 16283-2 (2015) for field measurements define the properties of the tapping machine more precisely, but the basic construction of the machine is still the same. The tapping machine was standardised in Germany in 1938 (DIN 4110). The German standard was also applied in some other countries, e.g. in Finland until the early 1950s (Arni 1949; Kylliäinen 2009). In Austria, the requirements for sound insulation between dwellings were standardised already in 1936 (ÖNORM B 2115), but the definition of the requirements did not include the tapping machine as a sound source.

According to DIN 4110 (1938), a total SPL at a frequency range from 600 to 1200 Hz was measured without frequency filtering in a receiving room when the tapping machine was operating in another dwelling. The measurement results were normalised to a reference absorption area A having a value of 1 m^2. Gastell (1936) discussed the advantages of a frequency analysis of the sound in the receiving room, but that was not adopted in the standard. Ingerslev *et al.* (1947) found that the German standard method was insufficient and unreliable without the frequency-band measurements. They suggested that the impact sound levels should be measured at 1/3-octave centre frequency bands at frequency range from 125 to 1600 Hz. In the first international conference on acoustics held in London in 1948, there was a suggestion of standardisation of the measurement method for impact sound insulation. The suggested frequency range was 50–1600 Hz and the measured SPLs would have been standardised to a reverberation time of 0.5 s (Beranek 1949).

The reference curve for rating the impact sound insulation of floors was first standardised in the 1950s in the German standard DIN 52211 (1953). The original idea of the reference curve was that it was given as constant levels and the measurement results were allowed to deviate from it not more than 2 dB on average. Later, when the reference curve was adopted to the standard ISO R717 (1968), the calculation method of the SNQ was changed. Now, the reference curve was moved in 1 dB steps until the mean unfavourable deviation is not more than 2 dB. The maximum unfavourable deviation was limited to 8 dB, but this rule was removed from the revised standard in 1982 (ISO 717-2). The basic idea of the reference curve method has remained similar since 1968 (Lietzén & Kylliäinen 2013) and is still in use as defined in ISO 717-2 (2013).

1.3 Problems of the standardised rating method

In 1949, before the first standardisation of the reference curve, Gösele defined the requirements for the SNQ which should be based on an objective sound source and measurement equipment, but the results determined by the objective method should correspond as well as possible to the occupants' subjective experience of loudness of sounds related to walking on a floor. In addition, the measured SNQs of two floors should be equal if these floors were judged subjectively similar (Gösele 1949). Mariner (1964) added one more requirement: there should be a method for converting the physical measurement results to a quantitative value corresponding to the subjective satisfaction with the impact sounds.

The tapping machine became internationally standardised when the standard ISO R140 was published in 1960. Mariner (1963) showed on the basis of listening experiments that the tapping machine sets the floors in a different ranking than the subjective judgement of floors based on real walking sounds. The tapping machine was also criticised because its loudness and sound spectra were considered to differ too much from the sounds generated by walking (Mariner 1964; Fasold 1965; Olynyk & Northwood 1965; Mariner & Hehmann 1967). It was also shown that no constant or formula can be derived that could in all situations be applied in the calculation of any walking spectrum at any floor from the spectrum generated by the tapping machine (Mariner & Hehmann 1967).

According to Gösele (1949), the tapping machine was originally defined so that the SPLs generated by it would be high enough to be measurable throughout the whole frequency range under interest. The difference between the living impact sounds and the tapping machine sounds would not be a problem if there were a method for calculating an SNQ from the measured tapping machine SPLs so that the result corresponds well with the subjective judgement of the floors (Gösele 1949, Mariner 1964). The contemporary authors of the 1960s stated that the reference curve first introduced in DIN 52211 (1953) was based on a floor which was proved satisfactory in practice (Cremer 1960; Fasold 1965; Mariner & Hehmann 1967). However, the problems with the standardised SNQs, $L'_{\mathrm{n,w}}$ and $L'_{\mathrm{n}T,\mathrm{w}}$, were detected already in the 1960s. They were noticed to correlate insufficiently with the subjective judgement of floors with respect to e.g. walking sounds (Watters 1965; Fasold 1965; Mariner & Hehmann 1967; Olynyk & Northwood 1968).

1.4 Alternative rating methods

Since the 1960s, there have been two strategies for solving the question about the rating method for impact sound insulation. The first of them attempts to find a sound source that would generate sound corresponding better with living impact sounds than the tapping machine. Several suggestions for modifying the standard tapping machine or replacing it with a new sound source have been made (Watters 1965; Lindblad 1968; Schultz 1976; Tachibana & Tanaka 1996; Jeon *et al.* 2006; Jeon *et al.* 2009; Lee *et al.* 2009; Ryu *et al.* 2011). The international standards (ISO 10140-3, 2010; ISO 10140-5, 2010; ISO 16283-2, 2015) now allow the use of the rubber ball in laboratory measurements. There is, however, some evidence indicating that the alternative sound sources to the tapping machine do not necessarily lead to a better association between the objective SNQs and subjective rating (Gover *et al.* 2011a and 2011b).

It seems probable that the tapping machine will remain as the official impact sound source (Rasmussen & Machimbarrena 2014). There is also a recent suggestion that modifying or replacing the standard tapping machine is not necessary. Instead, the problematics concerning the association between the present SNQs and subjective rating should be solved by defining a new SNQ based on the tapping machine as a sound source (Zeitler *et al.* 2013). This is the second strategy for developing a rating method for impact sound insulation. Several alternative SNQs for rating the impact sound insulation of floors have been suggested since the 1960s (Gösele 1965; Fasold 1965; Gerretsen 1976; Bodlund 1985; Hagberg 2010).

The insufficient association between the present SNQs and subjective annoyance seems to be linked with the Mariner's (1964) requirement dealing with the conversion of the physical measurement results to a SNQ corresponding to the people's subjective satisfaction with the impact sounds. Fasold (1965) derived an alternative (**Figure 2**) for the reference curve of DIN 52211 (1953) by measuring the SPLs of several impact sound sources. Thereafter, he calculated the difference between the measurement results and SPLs generated by the tapping machine. As a result, a mean value for the difference between the SPLs generated by the tapping machine and the actual impact SPLs was found. Adding these differences to subjectively acceptable SPLs at 1/3-octave bands in dwellings resulted in a new reference curve.

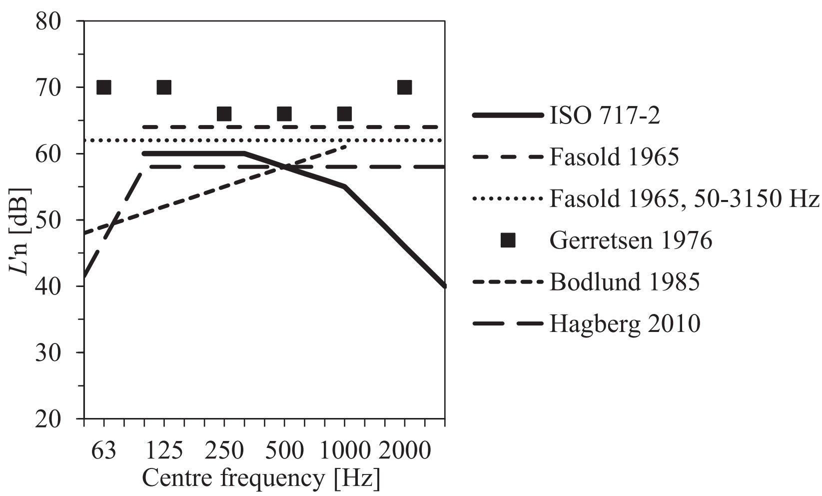

Figure 2. ISO reference curve and alternative reference curves for the rating of impact sound insulation.

Gerretsen (1976) also measured the differences of the SPLs between the tapping machine and walking. A new reference curve was derived by adding the measured differences to the values of the NR 45 curve, where NR refers to the Noise Rating (ISO R1996, 1971).

The reference curve suggested by Bodlund (1985) was based on the comparison of measured impact SPLs in the field with subjective rating by the people obtained by interviews. The best alternative reference curve was found by generating several guesses. Through a two-phase correlation analysis, the curve producing the best correlation was chosen to the suggested alternative for the ISO reference curve. The same materials added with some newer measurement results and the same method of generating guesses for an alternative reference curve was also used by Hagberg (2010).

The derivation of the four alternative SNQs reviewed above did not apply any mathematical optimisation methods. Furthermore, psychoacoustic laboratory experiments were not used even though they provide a possibility to study the annoyance of impact sounds in controlled conditions. Thus, the best possible reference curves have not necessarily turned up in the earlier studies. This may also explain why the suggested alternative reference curves and SNQs differ a lot from each other (**Figure 2**). There is a need for the development of mathematically justified SNQs for rating the impact sound insulation which would correlate better with the living impact sound types.

1.5 Psychoacoustic experiments

Fulfilling the requirements for the SNQ for rating impact sound insulation defined by Gösele (1949) and complemented by Mariner (1964) requires twofold research: in addition to the physical measurements of impact SPLs generated by the sound source, there is a need for psychoacoustic experiments concerning the subjective annoyance of walking and other usual living impact sounds. Mariner (1963) based his criticism towards the tapping machine on a listening experiment which included 30 participants who judged the sounds generated by the tapping machine and one walker on two floors.

The first psychoacoustic experiments in order to connect the measured impact sound insulation of floors with the subjective annoyance of transmitted impact sounds were conducted in the 1950s (Rademacher 1955; Rademacher & Venzke 1959). During the last few decades, some psychoacoustic experiments have also been carried out. However, many of the studies have aimed at some other objective rather than studying the association of the SNQs with the subjective annoyance of different impact sounds (Jeon & Jeong 2002; Jeon *et al.* 2004; Brunskog *et al.* 2011; Thorsson 2013). For example, in the extensively referenced work by Mortensen (1999), the objective was to study how different impact sound spectra are subjectively evaluated in relation to loudness, disturbance and annoyance. The connection with the SNQs of impact sound insulation was not studied. There is only a rather small amount of research focusing on the relation of the SNQs to the subjective rating of impact sounds.

Nilsson and Hammer (1999, 2001) studied how the SNQs for impact sound insulation and different objective noise and loudness rating methods correlated with subjective evaluation of impact sounds. The impact sound insulation of eight floor structures were measured in the laboratory and the following SNQs were calculated: $L_{n,w}$ according to ISO 717-2 (1996), $L_{n,w}$ with a limited maximum deviation of 8 dB from the reference curve (ISO R 717, 1968) and the SNQ suggested by Bodlund (1985). In addition to these, different noise and loudness ratings were defined. Two impact sound sources were used: female and male walker. Five of the eight floor structures were wooden floors and three were concrete floors. None of the floors had floor covering which means that neither the tapping machine spectra nor the walking spectra corresponded to the actual spectra of finished floors in buildings. A rather small number of participants, only 13 persons, listened to the sound samples via headphones. As the result of the study, the authors found that the SNQ defined by Bodlund (1985) gave the best correlation with a subjective evaluation of floors.

The structures in the studies by Gover *et al.* (2011a, 2011b) consisted of 19 different lightweight wooden floors. The floors were measured in the laboratory, and the SNQs according to standard ISO 717-2 (1996) were calculated. In addition to the tapping machine, the modified tapping machine as well as rubber impact ball (ISO 10140-5, 2010) and the Japanese bang machine with a tyre were used as sound sources in the objective rating. For the psychoacoustic tests, four sound sources were recorded: three adult walkers without shoes and dropping of an impact rubber ball from three heights. The psychoacoustic experiments were conducted with only 12 participants. As a conclusion, the authors state that the SNQs derived from the impact SPLs generated by the modified tapping machine do not correlate with the subjective rating of annoyance as well as the SNQs based on the SPLs generated by the standard tapping machine. It was also detected that the impact rubber ball gave a better correlation between the SNQs and the subjective rating of floors, but not necessarily better than the SNQs based on the standard tapping machine (Gover *et* *al.* 2011a). The authors stated that the highest correlation with a subjective rating were achieved with $L_{n,w} + C_I$ (Gover *et al.* 2011b). None of the 19 floors had a floor covering like carpet, laminate flooring or vinyl. This means that the relation of the results to real impact sounds in dwellings was not clear.

In the psychoacoustic experiment conducted by Späh *et al.* (2013), four wooden floors and one concrete floor were rated by the SNQs defined in the standard ISO 717-2 (1996). Alternative SNQs presented by Gösele (1965), Fasold (1965), Bodlund (1985), Hagberg (2010) and Ljunggren *et al.* (2013) were also calculated. In addition, the rubber impact ball and modified tapping machine (ISO 10140-5, 2010) were used as a sound source. In addition to the wooden floors, two types of concrete floors were measured: 140 mm thick concrete slab and this slab with a floating floor of 50 mm thick cast concrete on 25 mm thick mineral wool. Five floor coverings were used in all the tests. A part of the wooden floors was measured in the field, and the rest in the laboratory. For the psychoacoustic experiments, the walking of female and male walkers was recorded both in the laboratory and in the field. In the laboratory, the male walkers wore shoes and socks and the female walker hard-heeled shoes. Another impact sound source used in the psychoacoustic experiment was pulling a chair out. Two psychoacoustic experiments were made with 18 and 22 participants. From the SNQs based on the unmodified standard tapping machine, $L'_{n,w} + C_{I,50\text{-}2500}$ ($R^2 = 0.63$) and the SNQ suggested by Hagberg (2010) resulted in the highest correlation with a subjective rating ($R^2 = 0.58$).

On the basis of the recent psychoacoustic experiments, it is possible to conclude that the SNQs which were developed for the rating of heavy concrete floors in the 1950s are not necessarily applicable to the rating of lightweight floors. The survey in residential buildings by Ljunggren *et al.* (2014) also indicates that low frequency impact sounds are especially related to lightweight floors. Späh *et al.* (2013) state that an adequate SNQ for the rating of impact sound insulation should comprise all floor constructions, lightweight as well as massive floors. At the moment, a great majority of European dwellings are constructed of concrete or other massive structures (Rasmussen *et al.* 2014). There is earlier research referring to the importance of low-frequency sound in the case of certain heavy-weight floors (Hehmann 1964; Hehmann & Mariner 1965; Mariner & Hehmann 1967).

In the few works describing psychoacoustic experiments dealing with impact sound insulation, the connection to real floors in buildings is not always clear as the floors did not have any floor covering in many studies (Nilsson & Hammer 1999; Nilsson & Hammer 2001; Gover *et al.* 2011a; Gover *et al.* 2011b). The amount of impact sound types has also been limited: Nilsson & Hammer (1999; 2001) used only two sound sources. The variation of structural types of the floors has also been limited, as the focus has been on wooden floors in many studies (Gover *et al.* 2011a; Gover *et al.* 2011b; Späh *et al.* 2013). Therefore, there is a need for a psychoacoustic experiment concerning the impact sound insulation of concrete floors.

A reliable correlation analysis on the basis of a psychoacoustic experiment requires quite a large amount of data. In many of the psychoacoustic experiments referred to herein, the number of the participants has been rather small, approximately 20 persons or fewer (Nilsson & Hammer 1999; Nilsson & Hammer 2001; Gover *et al.* 2011a; Gover *et al.* 2011b; Späh *et al.* 2013). The risk of coincidence and resulting wrong conclusions increases with a decreasing number of participants. Considering airborne sound insulation, there is a recent study presenting the results of psychoacoustic experiments conducted with an extensive number of participants (Hongisto *et al.* 2014, 55 participants). Regarding impact sound insulation, it can be said that the scientific basis of the SNQs is insufficient. Thus, there is a need for a psychoacoustic experiment with a number of participants similar to that of Hongisto *et al.* (2014).

1.6 Measurement uncertainty and frequency range

During the formation of the rating method for impact sound insulation, the suggestion for the measured frequency range varied. Ingerslev *et al.* (1947) suggested that the lower limit of the measured frequency range should be set to 125 Hz because of the assumed increase in measurement uncertainty at lower frequency bands. In the international conference of 1948, the lower limit of the frequency range was suggested to be 50 Hz (Beranek 1949). Cremer (1960) claimed that measurements could not be done below 100 Hz without problems in measurement uncertainty. Fasold (1965) stated that measurements at frequency bands between 50 and 100 Hz might be significant, but this should be carefully considered because of increasing uncertainty.

It has long been recognised that in many cases the walking sounds at frequency bands below 100 Hz may have a remarkable effect on people's subjective rating of floors (Mariner 1964; Olynyk & Northwood 1965; Mariner & Hehmann 1967; Gerretsen 1976; Bodlund 1985; Blazier & DuPree 1994; Hagberg 2010). Since the 1990s, the ISO standards defining the measurement and rating methods have allowed for enlarging the measured frequency range down to 50 Hz in both airborne and impact sound insulation measurements (ISO 717-2, 1995; ISO 140-7, 1998).

However, many countries have not included this possibility in their national building regulation yet (Rasmussen & Machimbarrena 2014). The reason for this has apparently been the expected increase in measurement uncertainty due to the properties of the sound field (Pedersen *et al.* 2000; Hopkins & Turner 2005; Rasmussen & Rindel 2010).

There has been discussion on the measurement uncertainty in sound insulation measurements for a long time. The measurement methods are based on an assumption of a diffuse sound field, but it cannot be expected at low frequencies. For example, according to the formula derived by Schroeder and Kuttruff (1962), the limit of diffuse and non-diffuse sound fields is around 400 Hz in an empty room having a volume of 30 m^3. A substantial number of bedrooms in dwellings are of this size. In some studies, the accuracy of the measurements has been evaluated by determining standard deviations for the SPLs and reverberation times at the 1/3-octave centre frequency bands (Bodlund 1976; Olesen 1992; Göransson 1993; Simmons 2005). However, the derivation of confidence intervals or other statistical measures for the SNQs becomes difficult because of the reference curve method used in the calculation of the quantities. Therefore, the Monte Carlo method (Metropolis & Ulam 1949) has been used in the simulation of the distribution and uncertainty of the SNQs in some earlier studies. Normally, some generalised standard deviations like those presented in standards for the 1/3-octave band quantities have been used in the simulations (Goydke et al. 2003; Wittstock 2007; Navacerrada *et al.* 2008).

In the literature, most of the attention has been paid to the measurement uncertainty of airborne sound insulation at low frequencies in laboratory conditions (Pedersen *et al.* 2000; Goydke *et al.* 2003; Hopkins & Turner 2005; Simmons 2005; Wittstock 2007; Navacerrada *et al.* 2008; Hongisto *et al.* 2012). When judging the acceptability of a construction in a building or sound insulation between dwellings, a field measurement in a certain building between certain spaces is decisive. The acoustic characteristics of the rooms in field measurements are always different because of the varying shapes and volumes of the rooms. As the measurement uncertainty depends on them, an uncertainty evaluation based on standard deviations of measurands in one room is not exact when applied to another room. Thus, there is a need to study the measurement uncertainty of the SNQs including frequency bands 50, 63 and 80 Hz on the basis of field measurements.

1.7 Objectives

The main objective of this thesis was to develop new SNQs for rating the impact sound insulation of concrete floors. On the basis of some recent findings (Gover *et al.* 2011a; Gover *et al.* 2011b; Zeitler *et al.* 2013), the tapping machine will be used as an objective sound source in this study. The SNQs to be developed should proficiently explain the annoyance caused by impact living sounds transmitted from the neighbouring dwelling upstairs. Alternative SNQs concern five different impact sounds which were experimentally investigated. In addition, the purpose was to develop a SNQ that would explain the annoyance caused by all five impact living sounds.

In order to fulfil the purpose of the thesis, the research problem was divided into the following sub-problems:

- Measurements of the impact SPLs of a concrete floor covered with a wide scale of present-day floor coverings and floating floors
- Generation, measurements and recording of five spectrally different living impact sounds (walking with hard shoes, walking with socks, walking with soft shoes, super ball bouncing, chair moving)
- Noise rating i.e. objective methods for rating living impact sounds in order to find out whether it is necessary to study the concrete floors regarding to impact sound insulation
- Psychoacoustic experiment aiming to find out the associations between the subjective ratings of impact sounds and various standardised and alternative SNQs for objective rating of impact sound insulation
- Mathematical optimisation for defining new spectrum adaptation terms and reference spectra for rating impact sound insulation

Another objective of the thesis was to study the measurement uncertainties of the various SNQs for rating the impact sound insulation and find out how the increasing measurement uncertainty affects the deviation of SPLs at 1/3-octave bands as well as the deviation of the values of the SNQs.

2 MATERIALS AND METHODS

2.1 Structure of the research

The research problem and the sub-problems formulated in chapter 1.7 have been divided into five publications I-V as follows:

- **Publication I** describes the measurement of impact SPLs and SNQs of a concrete floor with various floor coverings and the generation and measurements of different living impact sounds. The publication also describes the methods and results of the noise rating of the living impact sounds.
- **Publication II** explains the recording of the living impact sounds and accomplishment and results of psychoacoustic listening experiment concerning the subjective rating of the living impact sounds and its association with various SNQs for the objective rating of impact sound insulation.
- **Publication III** presents the derivation of optimised reference spectra for rating the impact sound insulation from the results of the psychoacoustic listening experiment concerning the living impact sounds and objective impact sound insulation measurements with tapping machine as a sound source.
- **Publication IV** studies the measurement uncertainty of the standardised SNQs for rating the impact sound insulation on the basis of Monte Carlo simulations. The simulation concerns field measurements in 50 various spaces.
- **Publication V** describes an uncertainty study based on the Monte Carlo simulation of the laboratory measurements of nine concrete floors rated with the standardised as well as alternative SNQs of impact sound insulation.

The original publications I–V present the complete description of the materials and methods used in this research as well as the research results. The following chapters provide an overview of the entire study.

2.2 Optimised reference spectrum

2.2.1 Impact sound insulation measurements

The impact sound measurements were carried out at Upofloor laboratory in Nokia, Finland, where the bearing structure of the floor separating the vertically adjacent source and receiving rooms is a 265 mm thick concrete hollow core slab (400 kg/m^2). It was the most usual prefabricated slab type in Finnish apartment buildings during the 1980s and 1990s (Lietzén & Kylliäinen 2012). The measured reverberation times of the receiving room corresponded well with those of typical furnished rooms in Finnish dwellings (Takala & Kylliäinen 2013; Kylliäinen *et al.* 2016). Therefore, the sound spectra measured in the receiving room correspond well with the typical spectra in residential dwellings.

In the laboratory, all the floor coverings were installed in the same place on the slab. The size of the floor covering was 3.0 x 4.0 m^2. The floor coverings were installed as carefully as possible in order to avoid the effects of workmanship on the deviation of measured SPLs.

The study was conducted using a wide range of floor coverings in order to cover the typical impact sound insulation spectra found in dwellings. Eight different floor coverings on the bearing slab were used (**Table 1**). One measurement was also carried out without a floor covering (F1). In a laboratory test series, when floor coverings have to be quickly changeable, it was not possible to use cast concrete or cement screed as floating layers of floating floors. Thus, floating layers were constructed of a varying number of plasterboards and mineral wool layers with varying thicknesses in order to compose structures having different resonance frequencies at the frequency range below 100 Hz. Cushion vinyl or multi-layer parquet was used in order to achieve resonance frequency around 400–500 Hz. Moreover, very hard cushion vinyl and very soft floor-to-floor carpet were used.

The weighted reductions in impact SPL ΔL_w as shown in **Table 1** were defined according to standard ISO 717-2 (1996). The dynamic stiffnesses s' [MN/m^3] of the insulation layers of the floating floors were measured according to standard ISO 9052-1 (1989).

The measurements were carried out according to the field measurement standard ISO 140-7 (1998) as the laboratory constructed in the 1980s did not fulfil the present requirements for the laboratories in all respects. There were four fixed tapping machine positions on the floor of the source room and the sound generated by the tapping machine was measured in four fixed microphone positions. Two corner positions for loudspeakers were used in the reverberation time measurements. The number of the fixed microphone positions was four for each loudspeaker position. In each position, two decays were measured. The normalised impact SPLs L'_n were calculated from the spatial averages of 16 impact SPL measurements and 16 reverberation time measurements.

Table 1. Structural layers of the floor types denoted with letter F and a number 1–9.

Denotation	Structural layers of floor covering
Floor F1	No covering
Floor F2	Cushion vinyl, ΔL_w = 2 dB
Floor F3	Cushion vinyl, ΔL_w = 21 dB
Floor F4	Multilayer parquet 14 mm Soft underlay, ΔL_w = 20 dB
Floor F5	Wall-to-wall carpet, ΔL_w = 21 dB
Floor F6	Wall-to-wall carpet, ΔL_w = 37 dB
Floor F7	Multilayer parquet 14 mm Soft underlay 2 x plasterboard 15 mm (30 kg/m^2) Mineral wool 13 mm, s' = 16.1 MN/m^3
Floor F8	Multilayer parquet 14 mm Soft underlay 2 x plasterboard 15 mm (30 kg/m^2) Mineral wool 50 mm, s' = 11.5 MN/m^3
Floor F9	Multilayer parquet 14 mm Soft underlay 4 x plasterboard 15 mm (60 kg/m^2) Mineral wool 50 mm s' = 11.5 MN/m^3

The standardised SNQs were determined on the basis of the normalised impact SPLs L'_n. The weighted normalised impact SPLs $L'_{n,w}$ as well as the sum of $L'_{n,w}$ and spectrum adaptation terms C_I and $C_{I,50\text{-}2500}$ were calculated according to the standard ISO 717-2 (1996).

In addition to the standardised SNQs, four suggested SNQs were calculated. Reference curves defined by several authors were used. The standardised and alternative SNQ's were denoted as follows:

- $L'_{n,w}$ according to ISO 717-2 (2013)
- $L'_{n,w} + C_I$ according to ISO 717-2 (2013)
- $L'_{n,w} + C_{I,50\text{-}2500}$ according to ISO 717-2 (2013)
- $L'_{n,w,Fas}$ starting at 100 Hz (Fasold 1965)
- $L'_{n,w,Fas,50}$ starting at 50 Hz (Fasold 1965)
- $L'_{n,w,Ger}$ (Gerretsen 1976)
- $L'_{n,w,Bod}$ (Bodlund 1985)
- $L'_{n,w,Hag}$ (Hagberg 2010)

In the calculation of each SNQ, the maximum allowable sum of unfavourable deviations from the reference curve has been 32 dB, as Bodlund (1985) has shown that changing the evaluation rule by varying the sum of unfavourable deviations does not have a significant effect on the rating of the floors. In order to achieve a more precise understanding of the correlation between the SNQs based on the tapping machine and the SNQs based on walking, the principles of Wittstock (2007) were followed: the SNQs were defined by moving the reference curve in steps of 0.1 dB.

2.2.2 Measurements and noise rating of living impact sounds

The present standardised single-number quantities expect that the main impact source is walking with hard-heeled shoes. This sound type does not necessarily reflect the most typical impact sounds in all countries (e.g. Jeon *et al.* 2004; Gover *et al.* 2011a and 2011b; Ljunggren *et al.* 2014). Therefore, each of three male walkers W1, W2 and W3 (**Table 2**) wore socks, soft-heeled shoes and hard-heeled shoes. The same footwear was used through the test series. Each walker walked along a rectangular and an hourglass-shaped track on each floor covering. The SPLs were recorded in the receiving room at two microphone positions as a function of time with time weighting FAST. The measurement and walking duration were 40 seconds. The measured frequency range was 20–20000 Hz. All walking was performed twice.

Before calculating the noise ratings, the measured walking SPLs were background-noise corrected. Equivalent level of A-weighted background noise $L_{A,eq}$ was 17–18 dB. At 50 Hz, the background noise level was 20–25 dB which was well below the measured impact sounds. At the highest frequency range, the measured sound consisted in many cases of background noise only. This was the situation especially in the case of walking with socks and walking on floating floors and on softer wall-to-wall carpet.

Table 2. Description of the walkers. The shoe sizes correspond to the European measures.

Walker	Age	Mass	Height	Shoe size
W1	22	86 kg	188 cm	46
W2	40	125 kg	191 cm	44
W3	23	91 kg	183 cm	42

Background-noise corrected time-varying walking sounds were objectively rated by three noise ratings: equivalent A-weighted SPL, $L_{A,eq}$, calculated over the 40 s measurement period, maximum A-weighted SPL, $L_{A,F,max}$, and loudness level, L_N. Similar noise ratings have been used in the evaluation of walking sounds (Warnock 1992; Blazier & DuPree 1994; Mortensen 1999; Hammer & Nilsson 1999; Warnock 2000), even though the derivation of the rating from walking sounds may differ from the procedure presented here.

It is usually expected that the experienced loudness of a time-varying sound is determined by the loudest momentary spectrum (Zwicker 1977; Fastl & Zwicker 1997; Glasberg & Moore 2002). However, both $L_{A,F,max}$ and L_N vary frequently over relatively long time as each step generates a sound slightly different from other steps (**Figure 3**). For this reason, the momentary maximum spectra were selected from the time-varying sound pressure by calculating both $L_{A,F}(t)$ and $L_N(t)$ of the walking sound as functions of time. Depending on the walker, the typical number of maxima was 50–60 per each recording.

Plotting the spectra of all the momentary maxima of two repeated walks recorded in two measurement positions resulted in a sample of spectra based on either maximum A-weighted SPLs (**Figure 4**) or loudness levels. The sample size consisted typically of 200–250 momentary maxima. From these maxima, the typical spectra of each walking were calculated as energetic averages of the sample of the spectra. The results, i.e. $L_{A,F,max}$ and L_N, were then calculated from these energetic averages. The calculation of the loudness level $L_N(t)$ was carried out according to standard ANSI S3.4-2007, which includes the loudness model by Moore and Glasberg (Moore & Glasberg 1996; Moore *et al.* 1997) being the newest standardised model at the time when the study was conducted. The loudness levels were calculated on the basis of the SPLs at 1/3-octave bands in a frequency range of 50 Hz to 16000 Hz according to the standard.

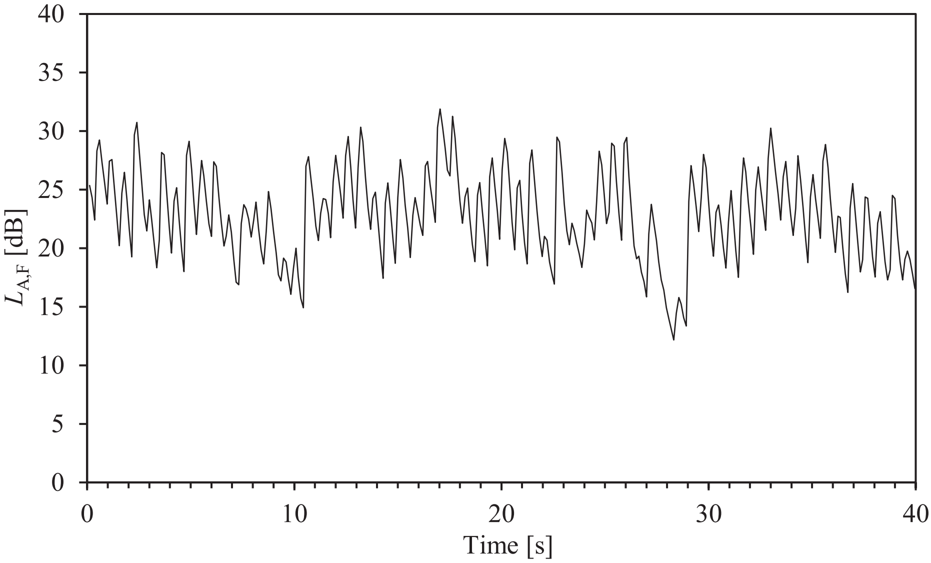

Figure 3. An example of the variation of $L_{A,F}$ generated by walker W1 wearing socks walking on floor F4. Each peak represents a momentary maximum (an individual step).

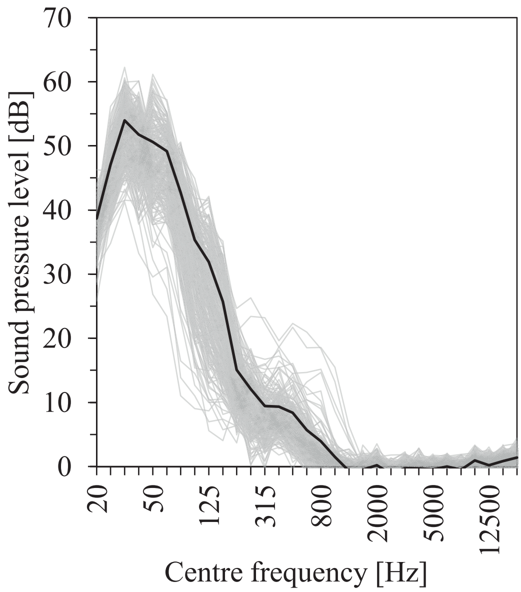

Figure 4. Examples of the spectra of momentary maxima of $L_{A,F}(t)$ described in Figure 3. The energetic average $L_{A,F,max}$ representing a typical step sound is shown with a black line.

There are several sources of impact sounds in dwellings like jumping, moving the furniture, falling objects or children playing. In addition to walking, two other impact sounds were studied here. The first represented one possible sound spectrum caused by playing children: a so-called super ball (weight 45 g) made of synthetic rubber and being very elastic was thrown towards the floor at the centre point of the floor covering. The bouncing was repeated so that the ball was turned back towards the floor from the same height (1 meter). Furthermore, the sound produced by moving a wooden chair was measured. The sound was generated as follows: first, a walker pulled the chair out from under a table, then the person moved to the front of the chair and moved it towards the table, sat down on the chair, stood up, pushed the chair away from the table and finally pushed the chair back under the table. In both cases, the measurement procedure was similar to the measurement of walking sounds.

The correlation between the noise ratings and the different SNQs based on the tapping machine were studied by calculating the squared Pearson product-moment correlation coefficients, i.e. the coefficients of determination R^2 for all the combinations of sound sources, footwear and floors.

2.2.3 Psychoacoustic listening experiment

In this experimental laboratory study, the participants judged recorded impact *sounds* in a psychoacoustic laboratory. The impact sounds were recorded in an impact sound insulation laboratory where nine floor constructions were installed one after the other (**floor types F1-F9**). Five different types of impact sounds (hereinafter referred to as "*sound types* S1–S5") were recorded for each floor type.

Several standardised and non-standardised SNQs were determined for each floor type based on their impact SPL measured using tapping machine as describer earlier in chapter 2.2.1. Thereby, the data could be used to determine how well the SNQs predict the subjective judgements of each sound type. The independent variables were the SNQs determined for the nine floor types and the five sound types. The dependent variables were two subjective measures: loudness and annoyance.

Fifty-five voluntary participants (25 male, 30 female) participated in the experiment. The age varied from 20 to 57 years (mean 27, median 25, standard deviation 9). The participants were invited via university student organisations. The participation requirements were normal hearing ability, Finnish native language and currently residing in a multi-storey building. The latter condition was judged as important because the experiment dealt with sounds usually heard in multi-storey buildings and so participants with no recent experience of living in such an environment were avoided. The participants were told that the purpose of the experiment was to evaluate different sounds. The participants were informed beforehand about the loudspeakers in the psychoacoustic laboratory.

After the measurements with the tapping machine, additional sound absorbers were installed in the receiving room of the impact sound laboratory to enable the sound recordings of natural impact sounds in such a room acoustic environment which resembles normal living rooms. The absorbents were placed on the floor and walls to achieve a reverberation time that corresponds relatively well with the reverberation time measured in Finnish living rooms and bedrooms (Takala & Kylliäinen 2013; Kylliäinen *et al.* 2016).

Five different impact sounds **S1-S5** (independent variable: *sound type*) were recorded in the laboratory for each floor type F1-F9. The *sound types* were:

- S1 – Walking with hard shoes
- S2 – Walking with socks
- S3 – Walking with soft shoes
- S4 – Super all bouncing
- S5 – Chair moving

The walker was in all cases a male person W1 (**Table 2**). The recordings of this walker were chosen for the psychoacoustic experiments as the loudest of the three walkers described in chapter 2.2.2. The two other walkers generated lower SPLs, but the shapes of the sound spectra generated by them were similar to the chosen walker.

Two-channel recordings were performed on the impact sound laboratory's receiving room. It has been suggested by Ljunggren *et al.* (2014) that the measurements of impact SPLs in determining the objective SNQ should be extended to 20 Hz. However, there is not enough evidence about measurement uncertainty below 50 Hz. In the materials of **Publication I**, the maximum SPLs, $L_{F,max}$, of impact sounds did not exceed the hearing threshold below 50 Hz in most cases (Lietzén 2012). Because of this, this study focused on the frequency range 50–5000 Hz. Lightweight constructions were not included in this study.

Simultaneously with the recordings of the five *sound types*, the equivalent SPL spectrum of the sound was measured to enable the identification and adjustment of the recording in the audio filtering stage. The background noise level $L_{A,eq}$ of the receiving room of the impact sound laboratory (absorbents installed) was 15.6 dB.

The peak levels of the stimuli (except sound type S3, walking with soft shoes) exceeded the background noise level of the psychoacoustic laboratory and the quality of the sounds was good for post-processing.

As a result of the recordings, twenty-second-long *experimental sounds* (hereinafter referred to as "*sounds*") were presented to the participants. The sounds are abbreviated by **FXSY**. Letter S refers to the *sound type* which had five values: X = 1 to 5. Letter F refers to the floor type which had nine values: Y = 1 to 9 (**Table 1**).

The experiment was conducted in the psychoacoustic laboratory (30 m^2) at the Finnish Institute of Occupational Health. The dimensions of the laboratory are: width 4.6 m, length 6.7 m and height 2.7 m. The volume of the psychoacoustic laboratory is 83 m^3. The background noise level $L_{A,eq}$ was measured using a highly sensitive condenser microphone. The background noise level $L_{A,eq}$ in the psychoacoustic laboratory corresponded with the mean value measured in Finnish living rooms (Takala & Kylliäinen 2013), but there were differences in sound spectra. In the psychoacoustic laboratory, the SPLs were higher at the low frequencies but lower at mid and high frequencies. The reverberation time corresponds well with the range measured in Finnish living rooms (Takala & Kylliäinen 2013; Kylliäinen *et al.* 2016).

The participants sat at the workstation during the experiment. The experimental sounds were reproduced by four active loudspeakers installed above the suspended ceiling in the periphery of the psychoacoustic laboratory. The levels of individual speakers differed less than 1 dB ($L_{A,eq}$). The speakers were not visible to the participants. In addition, one subwoofer was located on the floor behind a heavy curtain.

The sounds were played using a standard Windows player (Multimedia control). The playback computer was located behind the curtain 4 metres away to avoid the increment of background noise level. The computer was connected to a sound card, which controlled the four speakers and the subwoofer. The output levels of the four ceiling speakers were adjusted so that the SPL caused by each speaker was similar in the subject's position.

A software program was programmed in order to associate the playback of the sounds with the questionnaires to the participants. The subject controlled the experimental procedure (listening to sounds, answering the questionnaires, moving to the next sound) using this software.

The dependent variables of the experiment were three subjective measures: loudness, annoyance and acceptability. The participants were instructed in the following way before starting the experiment: "*Imagine that you are alone at home in a* *multi-storey building in silence and peace. You are in a relaxed mindset. You are reading a magazine or a book or you are browsing the Internet and you start to hear a sound from the neighbouring dwelling upstairs.*"

The background noise level of the psychoacoustic laboratory was larger than the equivalent level of several *experimental sounds*. However, the pilot tests indicated that nearly all the *experimental sounds* were audible because the stimuli were impulsive, and the *experimental sounds* originated from the ceiling so that the *sounds* were easily audible despite the low equivalent level.

To assure that the responses really represented audible experiences, the range of each subjective variable was expanded from that used by Hongisto *et al.* (2014) to also reveal the true audibility of each sound. If the subject judged the sound as inaudible, they were advised to select "0" in each response scale. The number of participants giving a notation of an inaudible sound was small. Inaudible ratings were mainly given for the *sounds* F6S2 (25 participants) and F9S3 (13 participants). For other combinations, inaudible ratings were only occasional.

Before enabling the judgement of the sound samples, the subject was forced to listen to the sound sample once which lasted 20 seconds. During this period, the sentence "*You hear this kind of sound coming from your neighbour*" was shown on the display. Thereafter, three questions appeared on the screen. The sound sample was repeatedly played until the responses were given.

The *loudness* rating was given after a question "*How loud is the sound?*" The judgement was given on a scale from "0" to "10". The extreme alternatives were verbally labelled by "0: The sound is not heard", "1: Very silent" and "10: Extremely loud". The participants were instructed to choose "0" if they could not hear the sound at all.

The *annoyance* rating was given after the question "*How annoying is the sound?*" The judgement was given on a scale from "0" to "10". The extreme alternatives were verbally labelled by "0: Not at all annoying because the sound is not heard", "1: Not at all annoying" and "10: Extremely annoying". The participants were instructed to choose "0" if they could not hear the sound at all.

The *acceptability* rating was given after the question "*Would the sound be acceptable if it could be heard in your own home?*" The judgement was given on a four point verbal scale: "0: Completely acceptable because the sound is not heard", "1: Completely acceptable", "2: Acceptable to some extent", and "3: Definitely not acceptable". A four-point scale was used since the purpose of this question was to enquire about the subject's ultimate opinion of the sound using a very simple verbal scale. Only the values of *loudness* and *annoyance* were reported in **Publication II** because the correlation coefficients of *acceptability* were very close to those of *annoyance* and the conclusions of the research would not be affected by including the *acceptability* data.

The experiment consisted of five phases: questionnaire, hearing sensitivity test, familiarising phase, rehearsal phase and experimental phase. The questionnaire and hearing sensitivity test were conducted in a silent semi-anechoic room. The hearing sensitivity test was carried out in order to check that the hearing ability was normal in the frequency range of interest. All the participants' hearing was within the normal range for both ears and no hearing loss was detected. Thereafter, the subject moved to the psychoacoustic laboratory.

The familiarising phase was used to let the subject to become familiar with the forthcoming *sounds* and their levels. This phase consisted of a collection of 15 *experimental sound* samples lasting only 8 seconds. Three samples of each of the five *sound type* were played. The most silent, the average level and the loudest *sound* were played in this order on the basis of the A-weighted levels. The participants were not yet given the possibility to judge the *sound* in the familiarising phase.

The rehearsal phase was for practicing the subjective rating. The rehearsal period followed the same procedure as in the experimental phase. Nine *sounds* were used. The results were not analysed. Before the rehearsal phase, the participants were instructed both orally and visually about the use of the rating scales. They were encouraged to use the whole scale.

The experimental phase consisted altogether of 60 experimental sound samples; 5 dummy sound samples (F0), experimental sound samples (nine floors per *sound type*), and the repetition of 10 experimental sound samples. The experimental sounds of each *sound type* were played successively in a cluster, preceded by one dummy sample (F0) and following by the nine *experimental sounds* (F1-F9). Finally, the first and the fourth *experimental sound* of each *sound type* in a cluster were presented again. This was done in order to obtain information concerning the repeatability of the ratings. The results of the repeatability tests are shown in **Publication II** and are not be repeated here.

The presentation orders of the *sound types* (S1-S5) and of the *floors* (F1-F9) were quasi-randomised between participants (Balanced Latin Square, five and nine alternative order choices respectively). Thus, all kinds of order effects were eliminated.

The dummy samples F0S1, F0S2, F0S3, F0S4 and F0S5 were used to give the participants some extra time to get used to the new *sound type*. The dummy sound sample for each sound type was created by setting the overall listening level L_2 of the sound involving the floor F4 exactly to 30 dB $L_{A,eq}$. Thus, the dummy sound did not correspond to any of the experimental sounds, but it resembled them to a great extent, as desired. The ratings of the dummy samples were not considered in the analysis.

The primary purpose of the study was to determine the linear correlation coefficients between the subjective measures and the SNQs of the floors for each *sound type*. The responses were not normally distributed. Therefore, the correlation analysis was not conducted using the mean of the subjective ratings which has been done usually (Gover *et al.* 2011; Hongisto *et al.* 2014; Bailhache *et al.* 2014). Instead, the correlation analysis was now conducted using every individual response instead of the mean of all responses. The resulting R-values are smaller compared to those which would have been achieved by using mean ratings. Pearson's correlation coefficients, R, were determined, and the coefficients of determination, R^2, were reported. The value of $100 \cdot R^2$ describes how many percent of the change in the subjective judgements can be explained by the change in the value of the SNQ. The correlation coefficient R was considered as statistically significant in the level of $p = 0.01$ (55 data points) when the value exceeds $R = 0.34$. The corresponding limit value for R^2 is 0.12.

2.2.4 Mathematical optimization

As a starting point for the development of the new SNQs for rating the impact sound insulation, it was assumed that they could be found by deriving a better reference curve or spectrum adaptation term instead of replacing the tapping machine with some other sound source. Thus, the new SNQs derived are based on the use of the standardised tapping machine as the sound source. A basis for the derivation of the new SNQs was that they can be expressed as the sum of $L'_{\mathrm{n,w}}$ or $L'_{\mathrm{n}T,\mathrm{w}}$ and a new spectrum adaptation term instead of C_{I} or $C_{\mathrm{I,50\text{-}2500}}$.

Experimental data utilised in this study originates from a psychoacoustic laboratory experiment explained in **Publication II** and chapter 2.2.3. The formulation of the optimisation problem is basically the same as developed by Virjonen *et al.* (2016). The detailed formulation is explained in **Publication III**. The calculation method for the SNQ, impact sound reduction index R_{impact} by Scholl (2011), was utilised instead of the formulation of ISO 717-2 ($L'_{\mathrm{n,w}}$ plus a spectrum adaptation term) since it is more appropriate for the optimisation purposes due to its explicit formulation. R_{impact} [dB] is calculated from impact sound reduction indices

R_i [dB] derived from the normalised impact SPLs $L'_{n,i}$ and reference spectrum levels L_i [dB]:

$$R_{\text{impact}} = 10\lg\frac{\sum_i 10^{L_i/10}}{\sum_i 10^{(L_i-R_i)/10}} \tag{1}$$

The connection between R_{impact} and $L'_{n,w} + C_{I,50\text{-}2500}$ has been given for standardised tapping machine by Scholl (2011). The goal was to find an optimal reference spectrum for each impact *sound type* S1–S5. The optimised reference spectrum for impact *sound type* S1 was called L_{S1}. Notation $R_{\text{imp\_S1}}$ was used for the SNQ which was optimised for impact *sound type* S1, etc.

The mean values of subjective annoyance given by the 55 participants for each floor type and sound type were used as a subjective variable in the optimisation problem since annoyance is closely related to health effects of noise and acoustic comfort. It was assumed that the subjective variable depends linearly on the SNQ. For each impact sound type, such a reference spectrum was sought wherein the subjective annoyance had the best achievable least-squares fit with the resulting SNQs. The optimal reference spectrum was determined by formulating the problem as a non-linear optimisation problem with constraints and solving it numerically (Bazaraa *et al.* 2013).

For the formulation of the optimisation problem, x_i is the SNQ of the floor type i (i = 1,…,9), and y_i is the subjective variable for the floor type i. Then, for the floor type i, the SNQ can be calculated from (Scholl 2011):

$$\mathrm{x}_i = 10\lg\frac{\sum_{j=1}^{K} 10^{L_j/10}}{\sum_{j=1}^{K} 10^{(L_j-R_{ij})/10}} = 10\lg\sum_{j=1}^{K} 10^{L_j/10} - 10\lg\sum_{j=1}^{K} 10^{(L_j-R_{ij})/10} \tag{2}$$

Lj is the level of the reference spectrum at frequency band j. That is, Lj values are optimised. R_{ij} is the impact sound reduction index for the floor i at frequency band j. The optimisation was made using third-octave bands from 50 to 2500 Hz, and thus, K = 18.

The impact source power level of the tapping machine is the reference spectrum for R_{impact}. For frequency band j, it is defined as (Scholl, 2011)

$$L_{\text{impact},j} = 82.1 + 10\lg\left(\frac{f_j}{1\ \text{Hz}}\right) \tag{3}$$

where f_j is the 1/3-octave centre frequency of the frequency band j. $L_{\mathrm{impact},j}$ was used as the initial guess for the algorithm, from which the algorithm started to proceed. The optimised reference spectra were normalised to the tapping machine's total impact power for the frequency range 50–2500 Hz:

$$10\lg \sum_{j=1}^{K} 10^{L_j/10} = 122.9\ \mathrm{dB} \tag{4}$$

The maximum level difference between adjacent frequency bands of the reference spectrum was limited to 5 dB to avoid too uneven reference spectra.

The optimised SNQ can be expressed as a sum of the weighted normalised impact SPLs $L'_{\mathrm{n,w}}$ and a spectrum adaptation term. E.g. spectrum adaptation term for impact sound S1, $C_{\mathrm{I,S1}}$, can be expressed as:

$$C_{\mathrm{I,S1}} = 10\lg \sum_{j=1}^{K} 10^{\frac{L_{S1,j}-78.2-10\lg f_j+L_{\mathrm{n},j}}{10}} - 18.9 - L'_{\mathrm{n,w}} \tag{5}$$

where $L_{\mathrm{n},j}$ is the normalised impact SPL for frequency band j.

The optimisation problem was solved using an algorithm for finding the minimum of a constrained nonlinear multivariable function (Matlab). The algorithm developed by Virjonen on the basis of her earlier work (Virjonen *et al.* 2016) works on the feasible area, i.e. the solution in each iteration fulfils the constraints. For each impact sound type, the algorithm stopped since the step size became smaller than the predefined tolerance. The solutions fulfilled the constraints. This means that a local minimum is possible. The calculation was also conducted with another initial guess, which led basically to the same results with all impact sound types.

In addition to sound type optimised reference spectra, an optimised reference spectrum over all five sound types was also derived. This is meaningful since the construction performances are declared using a single SNQ which is expected to represent all impact sound types sufficiently well. Therefore, all attempts to find SNQs that work for several impact sound types are worth investigating.

The optimised reference spectrum was called L_{opt} and the SNQ calculated from it $L'_{\mathrm{n,w}} + C_{\mathrm{I,opt}}$. This reference spectrum was derived by adding all the experimental *sound types* from all floors into the same pool. This was meaningful since all the experimental impact sounds were produced in the impact sound laboratory using normal forces (normal walking, normal super ball bouncing, normal chair moving) and the listening levels during the psychoacoustic experiment conformed exactly to the recorded levels.

2.3 Measurement uncertainty

2.3.1 Monte Carlo simulation

In acoustical research, the Monte Carlo method has been used since the 1950s (Allred & Newhouse 1958; Schroeder & Kuttruff 1962). The idea of the Monte Carlo method is that a value of a quantity is estimated on the basis of its variables receiving random values over a certain domain. The quantity is calculated by choosing one value for the variables over their domains. When the calculation is carried out repeatedly, a probability distribution of the quantity is achieved as a result (Metropolis & Ulam 1949).

The SNQ for judging the impact sound insulation of buildings, the weighted normalised impact SPL $L'_{n,w}$, is determined with the reference curve method. This makes is difficult to derive analytically confidence intervals or other statistical measures for the SNQs. Instead of an analytical solution, the measurement uncertainty was studied by the means of Monte Carlo simulation.

2.3.2 Simulations based on field data

All the measurements were carried out in pre-cast concrete buildings which are the most usual multi-storey building types in Finland. These buildings have load-bearing concrete elements as separating walls and usually concrete sandwich panels as outer walls. Non-bearing separating walls inside the apartments are mostly lightweight walls with timber or steel frame. Bearing structures of intermediate floors are hollow core slab fields or cast concrete slabs. Measured floors include all the typical Finnish floor structures of new apartment buildings. The measured floors have been put into five groups on the basis of floor covering as follows:

- floor type A: floor covering cushion vinyl, n = 11
- floor type B: floor covering multi-layer parquet with soft underlayment, n = 21
- floor type C: floor type B with suspended ceiling, n = 3
- floor type D: raised floor system with battens, n = 5
- floor type E: floating floor, n = 10

Within each floor type, there is variation as the bearing structure can be a hollow core slab or cast concrete slab and the mass of the slab varies as well. The mass of cast concrete slabs varied from 600 kg/m^2 to 750 kg/m^2. The mass of the hollow core slabs was 380, 400 or 510 kg/m^2. The weighted reduction of impact SPL ΔL_w of cushion vinyl and multi-layer parquet with soft underlayment has been 17–19 dB. The bearing structure of raised floors (type D) consists of steel or timber battens supporting a board structure on which the floor covering is installed. Within floor type E, the dynamic stiffness s' of the resilient layer of floors varied from 8 to 20 MN/m^3 according to the information given by the construction site. The mass of the floating layer varied from 40 kg/m^2 to 200 kg/m^2.

The measurements of normalised impact SPLs L'_n were carried out according to the standard ISO 140-7 (1998). Four tapping machine positions were used. Three random microphone positions per each tapping machine position were used. Two corner positions of loudspeakers were used in the reverberation time measurements. The number of random microphone positions was three per each loudspeaker position. In each position, two decays were measured. The average reverberation time was calculated from twelve decays. The equipment used in SPL and reverberation time measurements corresponded to the requirements of accuracy class 1.

All the measurements described in the data have been carried out in unfurnished rooms. The volume V of the rooms varied between 24 and 117 m^3. The amount of measured floor structures was 50. Most of the rooms were small: 32 measurements were done in rooms having a volume smaller than 40 m^3.

The standard ISO 140-7 (1998) required that the minimum number of measurements of SPLs is six so that the spatial average is a combination of four microphone and four tapping machine positions. In calculating the average of reverberation time, the minimum number of decays is also six. The average should be based on at least one loudspeaker position and three microphone positions. In each microphone position, two decays should be measured.

Instead of the minimum amount of SPL measurements and decays, 12 reverberation time and 12 impact SPL measurements were done. Following the rules presented in the standard, 20 averages $T_{sim,j}$ of reverberation times and 486 spatial averages $L_{k,sim,j}$ of impact SPLs per each measured structure could be calculated. In the Monte Carlo simulations, all the values of the variables were results from field measurements instead of random values selected within the range of the measured variables.

From the combinations of reverberation times $T_{sim,j}$ and impact SPLs $L_{k,sim,j}$, it was possible to calculate altogether 9720 combination curves $L_{n,sim,j}$ of normalised impact SPLs and impact sound reduction indices $R_{i,sim,j}$. From each of the simulated curves, the simulated values for the single-number quantities $L'_{n,w}$, $L'_{n,w} + C_I$, $L'_{n,w} + C_{I,50\text{-}2500}$ and R_{impact} could be determined. In order to achieve a more precise understanding of the uncertainty of the quantities, the work by Wittstock (2007) was followed: simulations were done by moving the reference curve in steps of 0,1 dB. The impact sound reduction indices were also rounded to 0.1 dB.

The uncertainty of the SNQs was evaluated as probability distributions of the deviations D_i between the single simulated values $X_{j,sim}$ and the mean value $X_{j,avg}$ of the simulated SNQs:

$$D_i = X_{j,sim} - X\mathrm{i,avg} \tag{6}$$

X refers to the studied SNQs i.e. $L'_{n,w}$, $L'_{n,w} + C_I$, $L'_{n,w} + C_{I,50\text{-}2500}$ and R_{impact}. The distributions D_i have been numbered in this order with numbers 1–4. In **Publication IV**, the results for the deviation D_3 ($L'_{n,w} + C_{I,50\text{-}2500}$) were not shown as the single-number quantity $L'_{n,w} + C_{I,50\text{-}2500}$ corresponds reversely to impact sound reduction index R_{impact} (Scholl 2011; Scholl *et al.* 2011). The only difference between the probability distributions of D_3 and D_4 (R_{impact}) is that the probability distribution of D_3 is reversed over the zero position.

2.3.3 Simulations based on laboratory data

Laboratory measurement data from the nine floors F1…F9 described in chapter 2.2.1 was used in Monte Carlo simulations dealing with the measurement uncertainty of standardised and alternative SNQs for rating the impact sound insulation. The alternative SNQs analysed were those described in chapter 2.2.1. In addition to that, the measurement uncertainty of the suggested SNQ (Scholl 2011), R_{impact}, was calculated. As stated in chapter 2.2.2, the standard deviation of its values corresponds to the $L'_{n,w} + C_{I,50\text{-}2500}$.

The laboratory measurements were carried out according to the standard ISO 140-7 (1998). More than the required minimum number of measurements were conducted so that there were 16 reverberation time measurements and 16 impact SPLs available. Following the rules presented in the standard, 56 averages of reverberation times and 1,656 spatial averages of impact SPLs per each measured floor covering could be calculated. The SNQs were then calculated by choosing one average for the reverberation time and one average for the spatial average of impact SPL. As a result, 92,736 normalised impact sound spectra could be simulated. All the values of the variables were results from measurements instead of random values selected within the range of the measured variables.

The uncertainties of the SNQs were evaluated as probability distributions of the differences D_i between the single simulated values $X_{j,sim}$ and the mean value $X_{j,avg}$ of the simulated SNQ as described in chapter 2.3.2.

3 RESULTS

3.1 Impact sound insulation of floors

The normalised impact SPLs generated by the tapping machine on the nine floors are shown in **Figure 5**. The SNQs calculated from them are given in **Table 3**. The range of investigated impact SPLs cover well the typical range found in buildings.

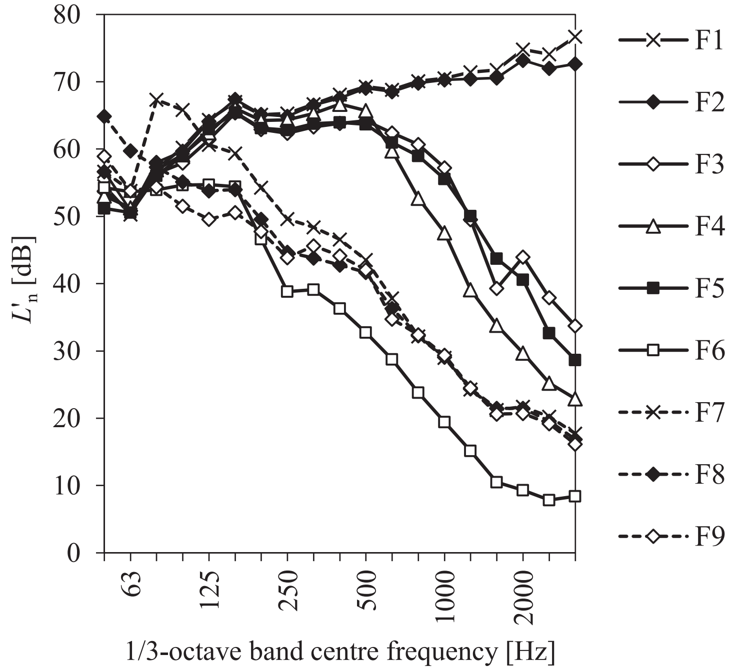

Figure 5. Normalised impact SPLs L'_n produced by the tapping machine placed on the nine floors.

Table 3. The standardised and suggested SNQs [dB] of the nine floors F1…F9 based on the tapping machine.

SNQ	F1	F2	F3	F4	F5	F6	F7	F8	F9
$L'_{n,w}$	79.9	77.7	58.7	59.1	58.5	42.7	50.1	43.2	41.3
$L'_{n,w} + C_I$	66.7	65.8	58.0	59.0	58.0	44.7	53.0	45.0	42.1
$L'_{n,w} + C_{I,50\text{-}2500}$	66.7	65.8	58.1	59.1	58.1	47.3	55.9	52.4	47.6
$L'_{n,Fas}$	68.4	67.3	59.4	60.4	59.4	44.7	52.1	45.2	43.0
$L'_{n,Fas,50}$	68.4	67.3	59.4	60.4	59.4	49.0	55.6	52.2	47.8
$L'_{n,Ger}$	66.4	65.6	58.4	59.8	58.6	41.9	50.3	43.6	41.5
$L'_{n,Bod}$	66.0	65.9	62.6	63.9	62.8	56.5	62.8	59.8	55.3
$L'_{n,Hag}$	68.7	67.8	60.7	61.8	60.5	54.5	61.2	61.0	56.1

3.2 Noise rating of living impact sounds

The mean spectra of walking based on the energetic averages of the momentary maxima of the time-varying $L_{AF,max}$ are shown in **Figure 6**. Similar curves could be drawn for $L_{A,eq}$ and for the momentary maxima of the time-varying loudness level L_N. The values of noise ratings based on these curves are given in **Table 4**.

The noise ratings of the super ball bouncing and the chair moving are also given in **Table 4**. The corresponding energetic averages of momentary maxima of time-varying A-weighted SPL are shown in **Figure 7**.

The calculated coefficients of determination R^2 between the noise ratings (**Table 4**) and the SNQs based on the tapping machine and the reference curves (**Table 3**) are given in **Table 5**. The sample size was 9 which means that R^2 values exceeding 0.34 have a significance level of $p < 0.05$ and R^2 values exceeding 0.56 have a significance level of $p < 0.01$.

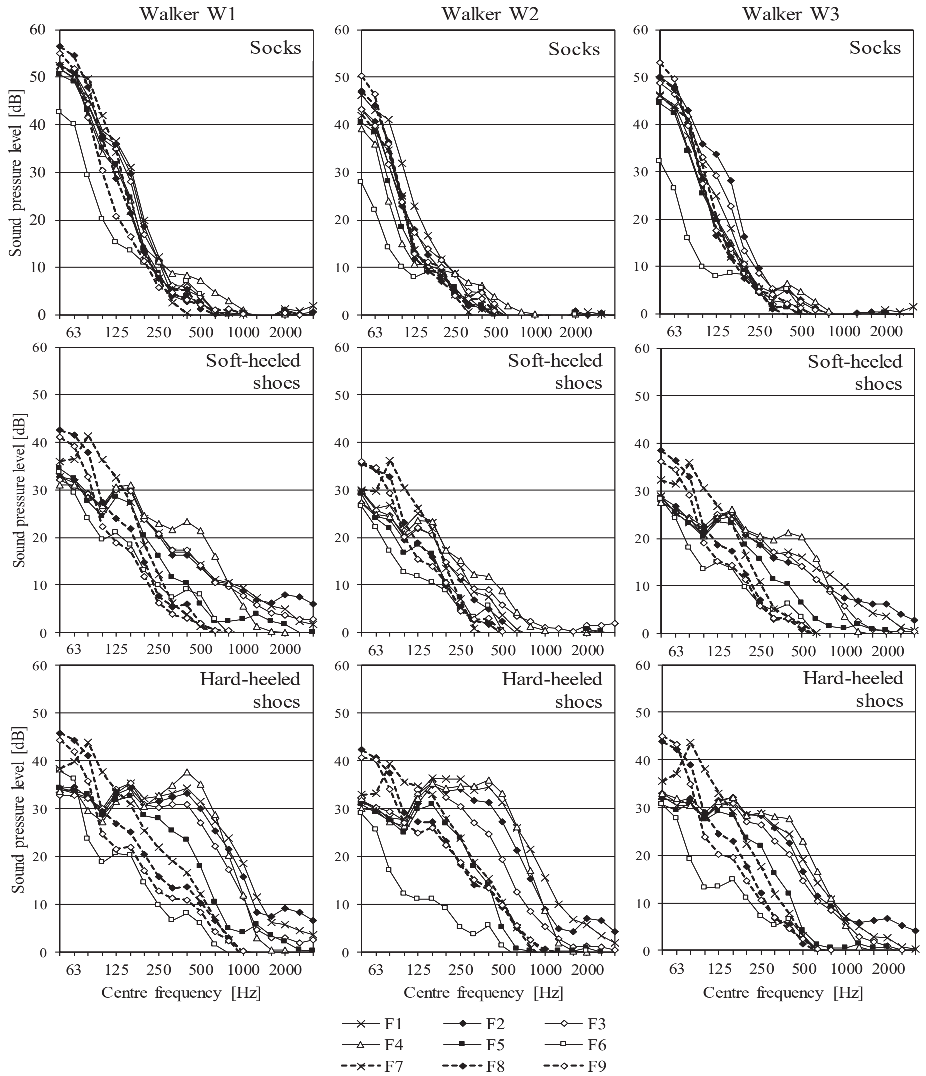

Figure 6. Energetic averages of walking sound spectra based on momentary maxima of $L_{A,F(t)}$ during 40 s.

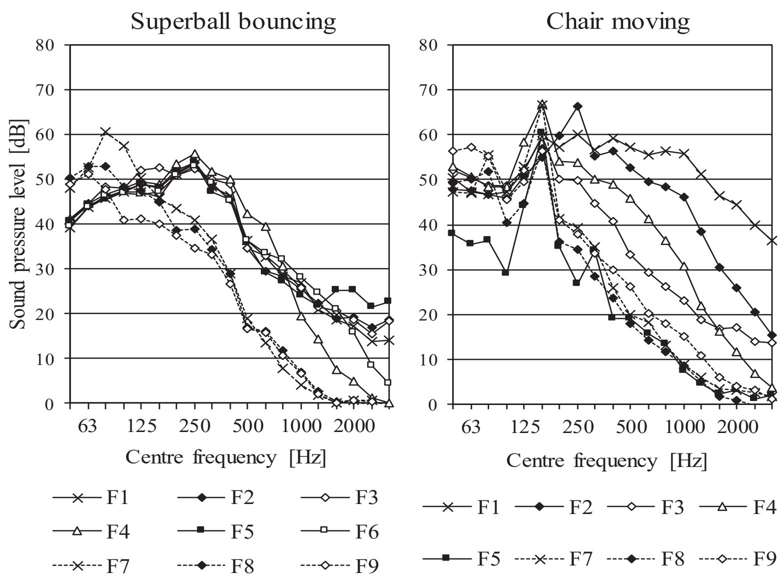

Figure 7. Energetic averages of sound spectra of ball bouncing and chair moving based on momentary maxima of $L_{A,F}(t)$ during 40 s.

Table 4. Noise ratings determined for the various impact sound sources for the nine floors F1…F9. The units of the SNQs are: dB for $L_{A,eq}$ and $L_{A,F,max}$ and phon for L_N.

Walker	SNQ	F1	F2	F3	F4	F5	F6	F7	F8	F9
W1, socks	$L_{A,eq}$	27.8	27.7	26.6	26.1	25.6	18.9	28.5	30.1	27.7
	$L_{A,F,max}$	30.6	30.2	29.3	28.5	28.1	21.1	31.4	32.6	30.2
	L_N	31.3	30.3	28.4	27.3	26.4	15.8	29.4	29.5	25.3
W2, socks	$L_{A,eq}$	18.1	18.1	18.0	16.0	16.4	12.7	17.3	20.8	23.3
	$L_{A,F,max}$	20.4	20.4	20.4	17.6	18.4	13.4	19.6	23.3	25.8
	L_N	16.0	16.8	15.5	13.9	13.7	13.1	14.3	17.5	19.4
W3, socks	$L_{A,eq}$	21.3	25.1	23.6	20.4	19.7	13.8	21.5	23.6	25.7
	$L_{A,F,max}$	23.6	27.8	25.9	22.8	21.9	15.1	24.0	26.0	28.2
	L_N	21.5	27.2	23.9	17.8	17.1	13.1	19.6	20.6	22.3
W1, soft-heeled shoes	$L_{A,eq}$	21.3	21.2	20.9	22.7	19.4	16.4	21.3	20.5	20.2
	$L_{A,F,max}$	23.7	23.8	23.4	25.8	21.1	17.7	24.0	22.3	21.4
	L_N	32.7	34.4	32.2	35.0	23.8	17.2	23.8	19.5	16.6
W2, soft-heeled shoes	$L_{A,eq}$	14.6	13.5	14.4	15.3	12.7	12.1	15.8	14.9	14.7
	$L_{A,F,max}$	16.9	15.3	16.5	17.5	13.7	12.7	18.7	16.4	15.9
	L_N	17.4	14.9	19.3	20.3	13.3	12.8	17.0	13.8	12.3
W3, soft-heeled shoes	$L_{A,eq}$	19.0	18.3	18.5	20.1	15.9	13.1	17.4	16.4	16.2
	$L_{A,F,max}$	21.9	21.2	21.2	23.4	17.8	13.9	19.5	17.9	17.4
	L_N	30.9	30.4	28.4	31.6	20.1	13.2	18.6	14.6	12.8
W1, hard-heeled shoes	$L_{A,eq}$	31.0	29.9	27.9	32.9	23.9	17.9	23.9	23.0	21.8
	$L_{A,F,max}$	35.2	33.9	32.0	37.2	27.2	19.3	26.8	25.0	23.4
	L_N	49.7	48.4	44.6	49.0	36.0	17.3	31.7	27.0	23.6
W2, hard-heeled shoes	$L_{A,eq}$	30.7	27.9	24.5	31.1	19.1	13.0	21.8	20.2	20.0
	$L_{A,F,max}$	35.6	32.8	29.0	36.1	23.0	13.8	25.9	22.7	22.0
	L_N	49.3	45.5	38.7	47.9	27.3	13.0	31.2	25.9	25.4
W3, hard-heeled shoes	$L_{A,eq}$	23.9	23.4	22.2	25.3	19.0	13.9	22.6	20.8	21.5
	$L_{A,F,max}$	27.4	27.0	25.2	28.9	21.7	14.9	25.6	22.7	23.1
	L_N	37.5	38.0	33.5	39.1	25.2	13.5	27.0	21.0	19.6
Super ball bouncing	$L_{A,eq}$	42.5	42.2	43.1	44.8	42.4	42.6	37.9	33.2	29.0
	$L_{A,F,max}$	49.0	49.2	50.0	52.0	48.9	48.8	43.6	39.0	35.1
	L_N	64.2	65.3	66.5	64.7	66.2	63.7	52.6	49.3	45.3
Chair moving	$L_{A,eq}$	59.8	55.3	44.5	52.4	42.8	-	49.3	40.5	40.3
	$L_{A,F,max}$	63.1	60.6	49.1	55.7	47.0	-	53.5	44.2	44.6
	L_N	82.5	76.3	63.6	69.0	51.3	-	58.1	49.6	54.6

Table 5. Coefficients of determination R^2 between the noise ratings and SNQs based on tapping machine. Values exceeding 0.34 are bolded and values exceeding 0.56 are also underlined. The units of the SNQs are: dB for $L_{A,eq}$ and $L_{A,F,max}$ and phon for L_N.

Sound source	Noise rating	SNQ based on tapping machine							
		$L'_{n,w}$	$L'_{n,w} + C_I$	$L'_{n,w} + C_{I,50\text{-}2500}$	$L'_{n,Fas}$	$L'_{n,Fas,50}$	$L'_{n,Ger}$	$L'_{n,Bod}$	$L'_{n,Hag}$
W1, socks	$L_{A,eq}$	0.05	0.04	0.14	0.04	0.08	0.05	0.14	0.28
	$L_{A,F,max}$	0.05	0.05	0.15	0.05	0.09	0.06	0.15	0.29
	L_N	0.33	**0.34**	**0.51**	0.33	**0.42**	**0.35**	**0.51**	**0.64**
W2, socks	$L_{A,eq}$	0.02	0.06	0.01	0.04	0.02	0.04	0.04	0.01
	$L_{A,F,max}$	0.01	0.03	0.00	0.02	0.01	0.02	0.01	0.02
	L_N	0.00	0.05	0.01	0.04	0.02	0.04	0.06	0.01
W3, socks	$L_{A,eq}$	0.04	0.02	0.07	0.03	0.04	0.03	0.04	0.15
	$L_{A,F,max}$	0.05	0.03	0.09	0.03	0.05	0.04	0.05	0.17
	L_N	0.26	0.18	0.27	0.19	0.23	0.19	0.17	**0.36**
W1, soft-heeled shoes	$L_{A,eq}$	0.22	0.28	**0.37**	0.28	0.31	0.31	**0.42**	**0.41**
	$L_{A,F,max}$	0.27	**0.37**	**0.45**	**0.36**	**0.38**	**0.39**	**0.52**	**0.45**
	L_N	**0.72**	**0.83**	**0.78**	**0.83**	**0.80**	**0.85**	**0.79**	**0.61**
W2, soft-heeled shoes	$L_{A,eq}$	0.00	0.00	0.02	0.00	0.00	0.00	0.04	0.06
	$L_{A,F,max}$	0.02	0.05	0.10	0.04	0.06	0.04	0.16	0.16
	L_N	0.19	0.33	0.29	0.32	0.29	**0.34**	**0.40**	0.19
W3, soft-heeled shoes	$L_{A,eq}$	**0.42**	**0.50**	**0.56**	**0.51**	**0.51**	**0.54**	**0.57**	**0.52**
	$L_{A,F,max}$	**0.49**	**0.59**	**0.63**	**0.59**	**0.59**	**0.63**	**0.65**	**0.56**
	L_N	**0.76**	**0.85**	**0.80**	**0.86**	**0.82**	**0.87**	**0.76**	**0.62**
W1, hard-heeled shoes	$L_{A,eq}$	**0.63**	**0.70**	**0.72**	**0.72**	**0.71**	**0.74**	**0.70**	**0.63**
	$L_{A,F,max}$	**0.66**	**0.75**	**0.76**	**0.76**	**0.75**	**0.79**	**0.74**	**0.64**
	L_N	**0.77**	**0.86**	**0.86**	**0.88**	**0.86**	**0.90**	**0.82**	**0.70**
W2, hard-heeled shoes	$L_{A,eq}$	**0.60**	**0.62**	**0.68**	**0.63**	**0.65**	**0.65**	**0.63**	**0.66**
	$L_{A,F,max}$	**0.63**	**0.68**	**0.73**	**0.68**	**0.70**	**0.71**	**0.70**	**0.69**
	L_N	**0.70**	**0.73**	**0.78**	**0.74**	**0.76**	**0.76**	**0.72**	**0.72**
W3, hard-heeled shoes	$L_{A,eq}$	0.30	**0.34**	**0.43**	**0.34**	**0.37**	**0.37**	**0.43**	**0.48**
	$L_{A,F,max}$	**0.39**	**0.45**	**0.54**	**0.45**	**0.47**	**0.48**	**0.54**	**0.55**
	L_N	**0.71**	**0.80**	**0.81**	**0.81**	**0.80**	**0.83**	**0.79**	**0.69**
Super ball bouncing	$L_{A,eq}$	**0.35**	**0.50**	0.33	**0.49**	**0.40**	**0.48**	**0.41**	0.14
	$L_{A,F,max}$	**0.38**	**0.53**	**0.35**	**0.52**	**0.42**	**0.51**	**0.42**	0.15
	L_N	**0.42**	**0.52**	**0.35**	**0.53**	**0.43**	**0.53**	**0.36**	0.14
Chair moving	$L_{A,eq}$	**0.76**	**0.71**	**0.77**	**0.68**	**0.75**	**0.65**	**0.69**	**0.78**
	$L_{A,F,max}$	**0.79**	**0.74**	**0.80**	**0.71**	**0.77**	**0.67**	**0.70**	**0.80**
	L_N	**0.79**	**0.68**	**0.72**	**0.69**	**0.73**	**0.66**	**0.54**	**0.71**

3.3 Correlation of subjective and objective rating

The R^2 values between the single-number quantities (SNQ) and subjective measures (*loudness, annoyance*) are shown in **Table 6** and **Table 7** for the five sound types.

Table 6. The R^2-values between the single-number quantities and subjective *loudness* for five sound types. Bolding indicates that the value was statistically significant ($p < 0.01$, limit value 0.12). *Sound types* were clarified in Ch. 2.2.3.

SNQ	Frequency range	Sound type				
		S1	S2	S3	S4	S5
$L'_{n,w}$	100–3150 Hz	**0.47**	0.03	**0.32**	0.11	**0.54**
$L'_{n,w} + C_I$	100–3150 Hz	**0.57**	0.05	**0.39**	**0.16**	**0.50**
$L'_{n,w} + C_{I,50\text{-}2500}$	50–3150 Hz	**0.56**	0.08	**0.37**	0.10	**0.53**
$L'_{n,Fas}$	100–3150 Hz	**0.57**	0.04	**0.38**	**0.16**	**0.50**
$L'_{n,Fas,50}$	50–3150 Hz	**0.55**	0.06	**0.37**	**0.13**	**0.53**
$L'_{n,Ger}$	63–2000 Hz*	**0.58**	0.05	**0.39**	**0.15**	**0.49**
$L'_{n,Bod}$	50–3150 Hz	**0.60**	0.11	**0.41**	**0.13**	**0.44**
$L'_{n,Hag}$	50–3150 Hz	**0.45**	0.10	**0.29**	0.04	**0.51**

*Octave bands

Table 7. The R^2-values between the single-number quantities and subjective *annoyance* for five sound types. Bolding indicates that the value was statistically significant ($p <0.01$, limit value 0.12). *Sound types* were clarified in Ch. 2.2.3.

SNQ	Frequency range	Sound type				
		S1	S2	S3	S4	S5
$L'_{n,w}$	100–3150 Hz	**0.41**	0.03	**0.26**	0.09	**0.52**
$L'_{n,w} + C_I$	100–3150 Hz	**0.50**	0.05	**0.32**	**0.13**	**0.47**
$L'_{n,w} + C_{I,50\text{-}2500}$	50–3150 Hz	**0.49**	0.08	**0.31**	0.08	**0.51**
$L'_{n,Fas}$	100–3150 Hz	**0.49**	0.04	**0.31**	**0.12**	**0.47**
$L'_{n,Fas,50}$	50–3150 Hz	**0.48**	0.06	**0.31**	0.10	**0.51**
$L'_{n,Ger}$	63–2000 Hz*	**0.51**	0.05	**0.32**	**0.12**	**0.45**
$L'_{n,Bod}$	50–3150 Hz	**0.53**	**0.12**	**0.35**	0.11	**0.43**
$L'_{n,Hag}$	50–3150 Hz	**0.40**	0.09	**0.25**	0.04	**0.51**

*Octave bands

3.4 Optimised single-number quantities

The mean annoyance for impact sound types S1–S5 is presented in **Figure 8a–8e** as a function of the standardised SNQ $L'_{n,w} + C_{I,50\text{-}2500}$. The mean *annoyance* for impact *sound types* S1–S5 is presented in **Figure 8f–8j** as a function of the *sound type* optimised SNQ.

The mean *annoyance* over all five impact *sound types* and all nine floor types as a function of optimised reference spectrum, $L'_{n,w} + C_{opt}$, is shown in **Figure 9**. The optimised reference spectra are shown in **Table 8**. The squared correlation coefficients between the standardised and optimised SNQs and the mean annoyance are given in **Table 9**.

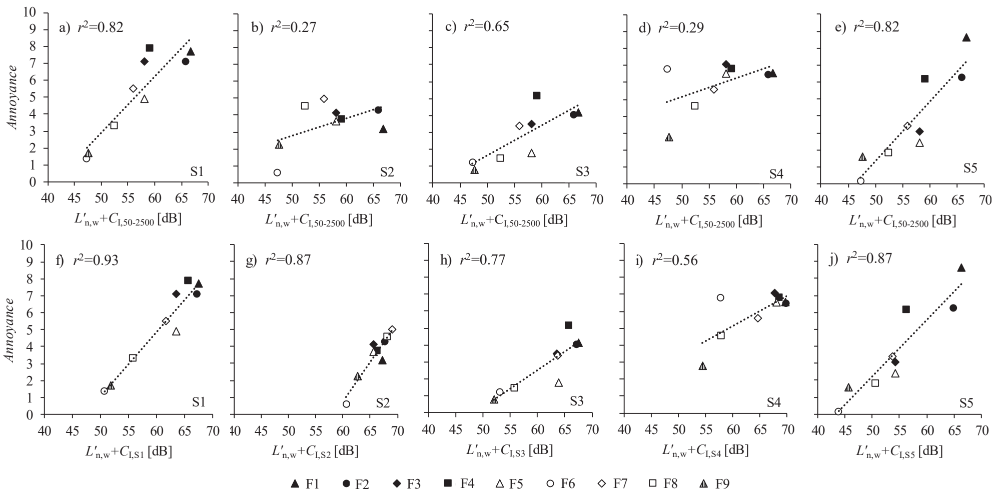

Figure 8. Mean annoyance for impact *sound types* S1–S5 and for floor types F1–F9 as a function of the standardised SNQ $L'_{n,w} + C_{I,50\text{-}2500}$ (panels a–e) and the sound type optimised SNQs $L'_{n,w} + C_{I,S1}$ … $L'_{n,w} + C_{I,S5}$ (panels f–j). The floors F1—F9 are indicated below. The squared Pearson's correlation coefficient, R^2, indicates the goodness of the linear fit between the observations.

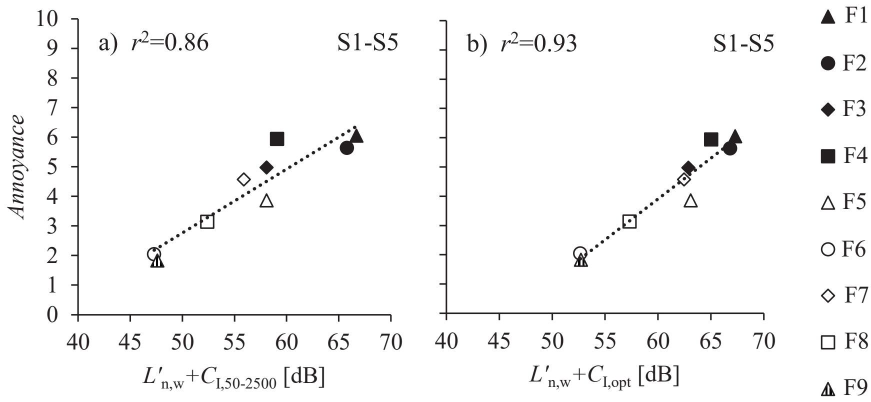

Figure 9. Mean annoyance over all five impact sound types and all nine floor types as a function of a) $L'_{n,w} + C_{I,50\text{-}2500}$ and b) optimised reference spectrum $L'_{n,w} + C_{I,opt}$. It should be noted that each observation represents the mean of five sound types while Figure 3 showed the means for each sound type, separately.

Table 8. The optimised reference spectra L_{S1}…L_{S5} for the calculation of spectrum adaptation terms of sound types S1–S5. The reference spectrum L_{opt} represents the optimised curve which fits well to all five sound types.

f [Hz]	L_{S1} [dB]	L_{S2} [dB]	L_{S3} [dB]	L_{S4} [dB]	L_{S5} [dB]	L_{Opt} [dB]
50	100	117	98	95	98	102
63	105	112	103	100	99	107
80	109	116	108	105	101	107
100	104	111	113	110	96	111
125	99	112	108	115	91	106
160	100	117	103	120	90	101
200	105	112	104	115	95	104
250	110	107	109	110	100	109
315	115	102	114	105	105	114
400	120	97	119	100	110	119
500	115	92	114	95	105	114
630	110	87	109	90	100	109
800	105	82	104	85	96	104
1000	100	77	99	80	101	99
1250	95	72	94	75	106	98
1600	90	67	89	70	111	103
2000	85	62	84	68	116	108
2500	80	57	79	69	121	113

Table 9. Squared Pearson's correlation coefficients R^2 of the optimised and standardised SNQs for each impact *sound type* S1…S5. The best acquired value per sound type is underlined.

SNQ	S1	S2	S3	S4	S5
$L'_{n,w} + C_{I,S1}$	<u>0.93</u>	0.38	0.75	0.35	0.73
$L'_{n,w} + C_{I,S2}$	0.41	<u>0.87</u>	0.30	0.01	0.31
$L'_{n,w} + C_{I,S3}$	0.91	0.35	<u>0.77</u>	0.42	0.69
$L'_{n,w} + C_{I,S4}$	0.87	0.24	0.71	<u>0.56</u>	0.59
$L'_{n,w} + C_{I,S5}$	0.75	0.26	0.61	0.20	<u>0.87</u>
$L'_{n,w} + C_{I,Opt}$	0.91	0.40	0.75	0.35	0.74
$L'_{n,w}$	0.68	0.09	0.54	0.30	0.80
$L'_{n,w} + C_I$	0.83	0.17	0.68	0.44	0.75
$L'_{n,w} + C_{I,50\text{-}2500}$	0.85	0.27	0.65	0.29	0.82

3.5 Measurement uncertainty

3.5.1 Effect of impact sound spectrum

The standard deviations of the simulated normalised impact SPLs $L'_{n,sim,j}$ are shown in **Figure 10**. Each point in the figure represents the standard deviation in a single measurement at a certain centre frequency. Each standard deviation represented by a dot in **Figure 10** has been calculated from 9,720 simulated values of the normalised impact SPL. The standard deviations of the simulated impact sound reduction indices $R_{i,sim,j}$ have not been shown because they are equal to those of $L'_{n,sim,j}$. The standard deviations of D_1, D_2 and D_4 have been shown in **Figure 11** for each of the 50 measured floors separately.

3.5.2 Dependence on the frequency weighting

From each simulated spectrum of L'_n of the nine floor structures, the eight SNQs and differences D_i were calculated. Standard deviations of the differences D_i of all SNQs are described in **Figure 12**. In the case of floors F1…F5, the standard deviations of D_i are below 0,45 dB for all SNQs. In this case, the differences between the standard deviations of D_i of all SNQs are within 0.3 dB. In the case of floors F6…F9, the standard deviations of D_i rise and the differences between the standard deviations D_i based on different SNQs also become larger. The largest difference between the standard deviations occurs in the case of floor F8.

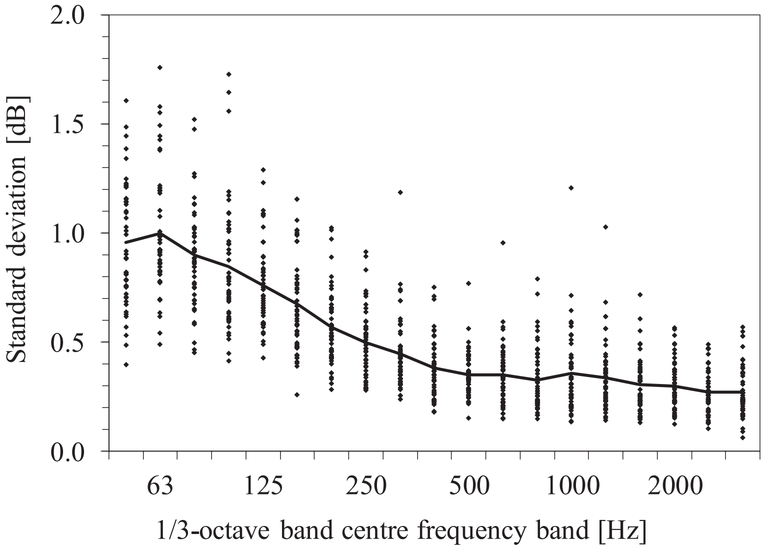

Figure 10. Standard deviations of simulated normalised impact SPLs $L'_{n,sim,j}$ in all 50 field measurements. The continuous line shows the mean of the standard deviations.

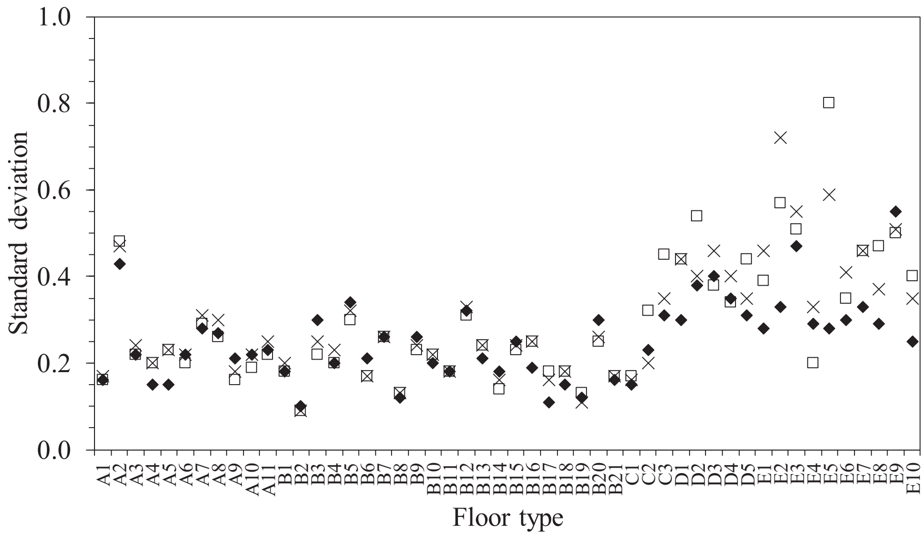

Figure 11. The standard deviations of differences D_1 (♦) for $L'_{n,w}$, D2 (×) for $L'_{n,w} + C_I$ and D_4 (□) for R_{impact} of simulated SNQs of each measured floor A1…E10.

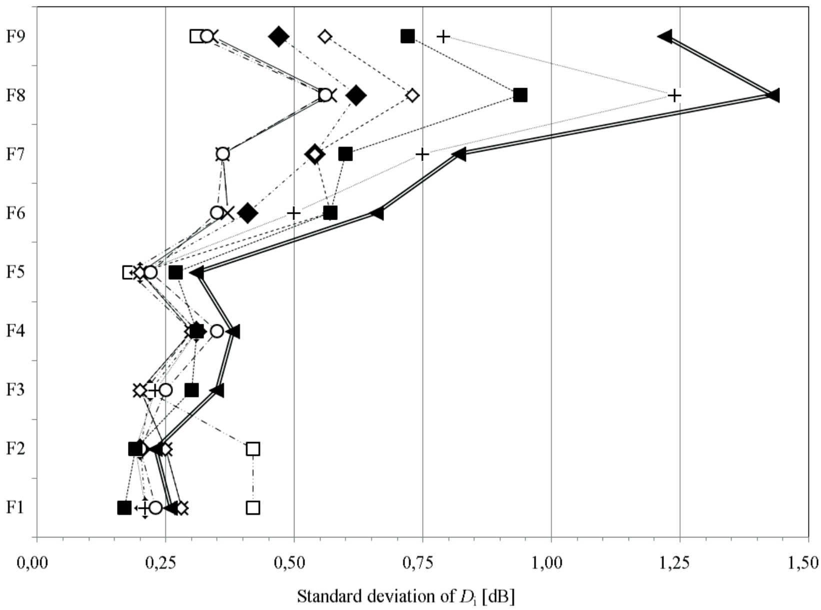

Figure 12. Standard deviations of D_i for all SNQs and all floors F1…F9. Markings: □ $D_{L'n,w}$, ♦ $D_{L'n,w+CI}$, + $D_{R impact}$, × $D_{L'n,Fas,100}$, ◊ $D_{L'n,Fas,50}$, ○ $D_{L'n,Ger}$, ■ $D_{L'n,Bod}$, ◀ $D_{L'n,Hag}$.

4 DISCUSSION

4.1 Sound spectra of walking on concrete floors

Walking with socks generated the highest SPLs below 200 Hz. Walking with hard-heeled or soft-heeled shoes also generated highest SPLs below 100 Hz, but hard-heeled shoes generated SPLs exceeding typical background noise levels of Finnish dwellings (Takala 2013) at frequency bands from 200 Hz to 1000 Hz as well. Below 100 Hz, the walking levels correspond to the levels measured by other researchers from walking on wooden floors (Warnock 1992; Blazier & DuPree 1994; Warnock 2000). This means that low-frequency walking sounds are not prevalent only with wooden floors, but they are also present with concrete floors.

In most Finnish dwellings, the background SPLs generated by HVAC systems are below 38 dB at 50 Hz and below 32 dB at 100 Hz. Below 100 Hz, most of the measured SPLs generated by walking with socks on all floors were greater than the levels of background noise in typical Finnish dwellings. The excess was 10–15 dB regarding walking with socks on floating floors and 5–10 dB regarding walking with hard-heeled shoes on floating floors. This indicates that walking on concrete floors (F7–F9) covered with floating floors might be a noticeable source of low-frequency sound. The results presented here are in agreement with earlier results (Hehmann 1964; Hehmann & Mariner 1965; Mariner & Hehmann 1967) even though the floor structures in the earlier studies have not been reported in detail.

It is noteworthy that walking with socks generated more sound below 100 Hz than walking with shoes. The level difference at the lowest frequency bands typically exceeded 10 dB except in the case of floor F6. It can thus be stated that walking with socks on concrete floors usually generates more sound in the low frequency range than walking with shoes. The result also indicates that walking with socks should be included in psychoacoustic experiments.

The bearing floor structure was the same 265 mm thick hollow core slab in all measurements. Other European countries use a wide scale of different concrete slabs with varying mass and stiffness (Rasmussen *et al.* 2014). The higher mass of the slab reduces the impact SPLs generated by the tapping machine. The changing mass and stiffness of the slab also influences the critical frequency of the slab. Both tapping machine and walking on other floors than those studied here might generate sound spectra differing from the spectra presented here. In most countries, however, the thickness, and mass of concrete slabs are quite similar to the one studied here (Rasmussen *et al.* 2014).

4.2 Noise rating versus single-number quantities

In recent studies concerning wooden floors (Gover *et al.* 2011a and 2011b; Späh *et al.* 2013; Ljunggren *et al.* 2014), concrete floors have been excluded or they have been used only as reference material to wooden floors. All the floors studied in this research can be considered as massive as they had a concrete slab as a bearing structure. The standardised and the alternative SNQs rated the measured floors mostly on the basis of the sounds generated at mid-frequencies by the tapping machine. This frequency range is significant regarding walking with hard-heeled shoes. The values of noise ratings based on walking, however, were often determined by the walking sounds in the low frequency range.

The noise ratings $L_{A,eq}$, $L_{A,F,max}$ and L_N based on the same walker (**Table 4**) wearing socks were similarly independent of floor structure. The within-walker differences were below 7.3 dB, 7.4 dB and 6.8 phon for $L_{A,eq}$, $L_{A,F,max}$ and L_N, respectively, for floors F1–F9 if floor F6 is ignored. For instance, walker W1 generated a maximum sound level $L_{A,F,max}$ of around 28–30 dB in the case of floors F1–F5 and around 30–33 dB in the case of floating floors F7–F9. The range of loudness levels L_N were 26–31 phon and 25–30 phon, respectively. In the case of walkers W2 and W3 wearing socks, there were results rating floating floors even louder than floors F1–F5.

In other words, the noise ratings based on walking with socks thus rate the floating floors equal to or louder than the bare concrete floor or floors with a light covering installed directly on the bearing concrete slab. The standardised and suggested SNQs based on the tapping machine, however, rate the best floating floor F9 about 10–38 dB better than the bare floor F1. As walking on floating floors F7-F9 generated more sound at low frequencies than walking on other floors (F1-F6), it can be concluded that low-frequency impact sound insulation of floors is not well included in the standardised or alternative SNQs (Fasold 1965; Gerretsen 1976; Bodlund 1985; Hagberg 2010).

Floor F6 had clearly lower noise rating values than the other floors (**Table 4**). When the standardised and suggested SNQs (**Table 3**) of floors F6 and F9 are compared with each other, the difference of the same SNQ is 2.6 dB at highest and 0.3 dB at smallest. The SNQs thus rated these two floors almost equal. In the case of walking with socks, floor F6 had 6–12 dB lower $L_{A,eq}$, 9–13 dB lower $L_{A,F,max}$ and 6–10 phon lower L_N than floor F9 had. On the basis of real walking sounds, floor F6 would obviously be a better structure than the objectively best rated floating floor F9. Thus, the ranking order according to the SNQs based on the tapping machine is incorrect in this respect.

Table 5 describes the coefficients of determination R^2 between the SNQs based on the tapping machine and noise ratings of walking and other impact sound sources. The correlation coefficients might give an impression that the SNQs described in the present standard, i.e. $L'_{n,w}$, $L'_{n,w} + C_I$ or $L'_{n,w} + C_{I,50\text{-}2500}$, are satisfactory as correlation coefficients between them and the noise ratings of walking with hard-heeled shoes exceed 0.60. $L'_{n,w} + C_I$ or $L'_{n,w} + C_{I,50\text{-}2500}$ correlate also well with the walking of W3 with soft-heeled shoes. Widest range of statistically significant correlation coefficients was achieved using $L'_{n,w} + C_I$, $L'_{n,Fas}$ and $L'_{n,Ger}$ which correlated strongly with the super ball bouncing in addition to the mentioned sound sources (**Figures 6** and **7**).

The SNQs based on the tapping machine had, however, mainly a weak correlation with noise ratings of walking with socks. This result supports the earlier researchers' (Hehmann 1964; Hehmann & Mariner 1965; Mariner & Hehmann 1967; Jeon *et al.* 2009; Warnock 1992; Hammer & Nilsson 1999) conclusions related to the significance of walking with socks and walking on concrete floors covered with floating floors. Most walking of the walkers W1 and W3 with soft-heeled shoes resulted in a statistically significant correlation, but the walking of walker W2 did not. The probable explanation to this is that the SPLs generated by W2 walking with soft-heeled shoes were lowest of the three walkers and W2 did not excite the resonance frequencies of floors F3, F4 and F5 like the other walkers did. This shows that in the walking tests, more than one or two walkers are needed in order to avoid false conclusions. Nearly half of the correlation between the objective SNQs and the noise ratings of walking with soft-heeled shoes were, however, weak.

The results described in **Table 5** indicate that both the standardised SNQs defined in the present standard and the alternative SNQs do not correlate well with the noise ratings of walking with socks or soft-heeled shoes. This means that both standardised and alternative SNQs ignore the meaning of walking with socks as a sound source. This confirmed that there was an obvious need for a new SNQ which would take walking with socks better into account.

4.3 Psychoacoustic experiment

The levels of *experimental sounds* were relatively low. A conscious risk was taken, as the sounds having a lower equivalent level than the background noise level of the psychoacoustic laboratory were included. Despite this, most of the *experimental sounds* were judged audible because the peaks of the sounds were clearly noticeable. The annoyance of the *experimental sounds* obtained in most cases a slightly higher mean rating than loudness. Therefore, it is suggested that the design of the experimental sounds and the prevailing masking sound is ecologically valid.

Two groups of *sound types* could be detected. The first group consists of *sound types* S1 (hard shoes), S3 (soft shoes) and S5 (chair moving) where statistically significant correlation was found between the SNQs and subjective measures. The other group consists of *sound types* S2 (socks) and S4 (super ball bouncing) which were subjectively rated so that very weak correlation between the SNQs and subjective measures was found.

The best indicators of subjective loudness and annoyance regarding *sound types* S1, S3 and S5 were $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$, $L'_{\mathrm{n,w}} + C_{\mathrm{I,50\text{-}2500}}$, $L'_{\mathrm{n,Fas}}$, $L'_{\mathrm{n,Fas,50}}$, $L'_{\mathrm{n,Ger}}$ and $L'_{\mathrm{n,Bod}}$. For *sound type* S5, the best indicator was $L'_{\mathrm{n,w}}$. On the basis of average correlations of S1, S3 and S5, the highest R^2 values (0.49) regarding subjective *loudness* were achieved with $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$, $L'_{\mathrm{n,w}} + C_{\mathrm{I,50\text{-}2500}}$ and $L'_{\mathrm{n,Ger}}$. Associating with subjective *annoyance*, the best averages (0.44) were achieved with $L'_{\mathrm{n,w}} + C_{\mathrm{I,50\text{-}2500}}$ and $L'_{\mathrm{n,Bod}}$. As $L'_{\mathrm{n,w}} + C_{\mathrm{I,50\text{-}2500}}$ is among the best associated SNQs with both subjective measures, it could be suggested to be the most suitable SNQ if *sound types* S1, S3 and S5 were considered as the most important impact sound sources. This is supported by the results of other studies dealing with lightweight structures (Späh *et al.* 2013; Ljunggren *et al.* 2014). The differences between the SNQs were, however, small and practically as good SNQs might be $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$, $L'_{\mathrm{n,Fas}}$, $L'_{\mathrm{n,Fas,50}}$, $L'_{\mathrm{n,Ger}}$ and $L'_{\mathrm{n,Bod}}$.

The lowest average R^2 values concerning *sound types* S1 (hard shoes) and S3 (soft shoes) were associated with $L'_{\mathrm{n,w}}$ and $L'_{\mathrm{n,Hag}}$. $L'_{\mathrm{n,w}}$ does not take the frequencies below 100 Hz into account or weigh large deviations from the reference curve in the way of $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$. This indicates that including the frequency range 50–100 Hz into a SNQ results in a better correlation between the SNQ and subjective rating also in the case of concrete floors. However, $L'_{\mathrm{n,Hag}}$ which gives the strongest weight to the low frequencies did not correlate well with the subjective ratings of *sound types* S1 or S3. This might suggest that the low frequencies perhaps should not be weighted too much either.

The low correlation between all SNQs and subjective ratings of *sound type* S2 (walking with socks) can probably be explained on the basis of sound spectra. In the case of *sound types* S1, S3 and S5, the sound spectra were dependent on the floor type (**Figure 6**). Thus, the correlation between the SNQs and subjective rating were statistically significant (**Figure 8**). The spectra and SPLs of *sound type* S2 are much less dependent on floor covering (**Figure 7**) than for other *sound types*. The difference between the highest and the lowest value of each SNQ was, however, large, between 10 and 38 dB depending on the floor type. Therefore, it is consistent that the correlation between the subjective rating of *sound type* S2 and SNQs was smaller than for other *sound types* where the spectral differences of the *experimental sounds* were larger (**Figure 9**).

Another difference between *sound type* S2 (walking with socks) and the other *sound types* was the shape of sound spectrum. Other *sound types* involved sounds at mid-frequencies in addition to low frequencies. Walking with socks generated the highest SPLs below 100 Hz with all floor types. This is quite similar to the spectrum of impact rubber ball used in Japan and South Korea which also generates dominant SPLs at frequencies below 100 Hz (Jeon *et al.* 2006; Lee *et al.* 2009; Ryu *et al.* 2011). In the referred Korean and Japanese studies, it has been found that subjective rating of impact ball is highly correlated with A-weighted maximum sound level $L_{\mathrm{AF,max}}$.

The result concerning *sound type* S4 (super ball bouncing) differed from the result presented in the **Publication I**. The analysis in **Publication I** was based on maximum sound spectra and loudness of the sounds only, and both of these objective ratings of super ball bouncing usually led to strong correlation with the SNQs. Temporal effects were not taken into account in **Publication I** as it is usually expected that the experienced loudness of a time-varying sound is determined by the loudest momentary spectrum when the temporal modulation frequency is less than 10 Hz (Zwicker 1977; Fatsl & Zwicker 1997; Glasberg & Moore 2002). Super ball bouncing differed from walking as the ball hit the floor around 0.7 times per second, but the frequency of steps was twice as large. Other explaining factor for low correlation between *sound type* S4 and subjective rating is similar to *sound type* S2: according to **Figure 6**, the spectra are quite equal to each other for floor types F1–F6 even though the corresponding values of the SNQs differ by 10 to 27 dB.

It is not absolutely clear which of the three subjective measures (*loudness*, *annoyance*, *acceptability*) is the most important in a residential environment. Several researchers have focused on loudness since various objective representatives have been published to predict subjective loudness (Tachibana *et al.* 1993; ANSI S12.2, 2008). *Loudness* is conventionally used for evaluating the overall level of clearly audible and loud sounds. It seems probable that loud neighbour sounds seldom exist in living environments on a continuous basis, nor in this experiment. The impression is that *annoyance* and *acceptability* judgements give more information about the potential negative effects of neighbour sounds which are relatively silent but contain information which may disturb the task at hand. This is perhaps supported by the proportion of subjective judgements rating *annoyance* with larger value than *loudness*. The proportion was 75 %, even though the difference between the values of ratings was usually small, the maximum being 0.71. This had also an influence on the correlation between the SNQs and subjective rating. Regarding especially *sound types* S1, S3 and S5, the correlation between the SNQs and subjective *annoyance* were in most cases somewhat lower than the correlation between the SNQs and subjective *loudness*. It seems that the SNQs explain the subjective loudness better than subjective *annoyance*.

It is difficult to compare the results of this study with earlier research as the number of participants and *sound types*, the generation of experimental sounds and floor types are different. The result of this study differs from that obtained by Späh *et al.* (2013) as they found that $L'_{n,Hag}$ was the best descriptor for walking noise. The next were $L'_{n,w} + C_{I,50\text{-}2500}$ and $L'_{n,Bod}$ which were among the best SNQs also in this study. Gover *et al.* (2011a and 2011b) found that $L'_{n,w}$, $L'_{n,w} + C_I$ and $L'_{n,w} + C_{I,50\text{-}2500}$ are well correlated with subjective annoyance of walking with socks, $L'_{n,w} + C_I$ being the best. Other SNQs were not included in their study. The R^2 values in their study were high, over 0.80. This might be explained by the fact that Gover *et al.* calculated correlations from mean ratings and not from all individual responses, as was done in this study. Only wooden floors were included in their study which may explain the difference between their and results of this study where the correlation between the SNQs and subjective loudness or annoyance from walking with socks was insignificant.

The age distribution of the experiment participants was centred on mainly young people in their twenties. This is, however, a common feature of psychoacoustic experiments generally (Mortensen 1999; Jeon & Jeong 2002; Jeon *et al.* 2004), and often the age and gender of the participants has not been reported at all (Nilsson & Hammer 1999; Nilsson & Hammer 2001; Gover *et al.* 2011a and 2011b; Späh *et al.* 2013). On the basis of earlier psychoacoustic experiments, it is not known whether age or other individual factors of the participants affects the subjective rating of impact sound insulation. This study, however, has a strong statistical power as the number of the participants exceeds twice or more the usual number (Mortensen 1999; Nilsson & Hammer 1999; Nilsson & Hammer 2001; Gover *et al.* 2011; Späh *et* *al.* 2013). One benefit of this study is the background of the participants. Instead of researchers, they were people living in dwellings in multi-storey buildings. They were familiar with the soundscape of such buildings. The distribution of the gender of the participants was better represented than age as 45 % of the participants were male.

The psychoacoustic experiment concerned massive floors only. This could be considered either as a weakness or as a strength. SNQs have not been compared with each other on the basis of psychoacoustic experiments of concrete floors as extensively as in this study. The floors in this experiment were all measured, and they were all realistic regarding the structural types used in modern buildings. All the sound types were also recorded instead of using artificially produced sounds.

The strength of this study is the large number of impact sound types. The number was larger than in psychoacoustic experiments usually (Mortensen 1999; Nilsson & Hammer 1999; Nilsson & Hammer 2001; Jeon & Jeong 2002; Jeon *et al.* 2004; Gover *et al.* 2011a and 2011b; Späh *et al.* 2013). The differences in correlation between the SNQs and the subjective rating of different sound types show that a psychoacoustic experiment cannot be based on one or two sound impact sound sources only.

The lowest frequency band included in this study was 50 Hz even though it is known that real impact sounds may include audible sounds below 50 Hz also in the case of concrete floors (Ford & Warnock 1974; Li *et al.* 1991; Warnock 1992; Langdon *et al.* 1993). It has recently been suggested by Ljunggren *et al.* (2014) that impact sound insulation measurements should be extended to 20 Hz especially when the lightweight floors are concerned. However, the SNQs applied in this research do not consider frequencies outside this range. Furthermore, the recorded maximum SPLs $L_{F,max}$ of the sounds exceeded the hearing threshold below 50 Hz at some frequency band only in a few cases of the recordings (Lietzén 2012). Therefore, it was absolutely justified to filter out all the sounds which did not belong to the investigated bandwidth, whatever happens in field conditions.

The psychoacoustic experiment has shown that the low frequency impact sounds are significant in the subjective rating of concrete floors. However, based on the psychoacoustic experiments dealing with lightweight floors, it seems possible that the subjective rating of lightweight floors might be based on some other phenomenon than rating of concrete floors. It would nevertheless be impractical to have various SNQs for different floor types. Therefore, it is reasonable to extend this study to cover lightweight floors applying the same methods.

4.4 Optimised single-number quantities

The materials of the psychoacoustic experiment were utilised in development of new reference curves which would explain the annoyance and loudness of different impact sounds better than the present SNQs. An optimised reference spectrum with high correlation with annoyance could be derived for each *sound type* S1–S5. Compared with the SNQs presented in the standard ISO 717-2 (2013), each optimised reference spectrum produced a higher correlation coefficient between the single-number quantity and the subjective judgement of the annoyance. Similar results have been achieved also in the case of airborne sound insulation (Virjonen *et al.* 2016). This shows that the mathematical optimisation is a consistent and justified method in striving for SNQs associating the physical measurement results to the subjective annoyance of the impact or other sounds.

Walking with socks (*sound type* S2) is among the most important impact sounds (Jeon *et al.* 2004; Gover *et al.* 2011a and 2011b; Ljunggren *et al.* 2014). Thus, the standardised SNQ should be well associated with the annoyance of this sound type. The experimental data in **Publication II** used in the optimisation shows that none of the studied standardised SNQs correlated well with the experienced annoyance of walking with socks.

It is very important that a reference spectrum with a high correlation with annoyance also for *sound type* S2 could be found using the optimisation method. The squared correlation coefficient was 0.87 being significantly higher than those of the standardised single-number quantities $L'_{n,w}$, $L'_{n,w} + C_I$ and $L'_{n,w} + C_{I,50\text{-}2500}$ (R^2 values within 0.09–0.27). Most importantly, all the *sound type* optimised reference spectra gave better squared correlation coefficients than any of the standardised SNQs.

The optimised reference spectrum for *sound type* S4 (super ball bouncing) produced a better correlation ($R^2 = 0.56$) than the standardised single-number quantities $L'_{n,w}$, $L'_{n,w} + C_I$ and $L'_{n,w} + C_{I,50\text{-}2500}$. However, the squared correlation of *sound type* S4 is clearly lower than for the other *sound types*. One reason might be the narrow spread of annoyance responses. However, this cannot be the only reason since equally narrow spread was observed also for *sound types* S2 and S3. The reason for low correlation seems to be floor type F6 involving a very soft wall-to-wall carpet. It produces a low SNQ value but the *sound type* S4 is subjectively judged quite annoying. The soft wall-to-wall carpet leads to the lowest SPLs from walking (S1–S3) and chair moving (S5), but S4 is an exception. This *sound type* S4 with wall-to-wall carpet generates similar impact sound spectrum as this *sound type* with floors F1–F5 explains this exception.

The optimisation problem was first solved separately for five *sound types* S1–S5. It was found important to derive a single reference spectrum that would explain the annoyance responses reasonably for all five *sound types* simultaneously. Therefore, an optimised reference spectrum, L_{opt}, was also presented in order to predict the annoyance of all five *sound types*. The optimised reference spectrum is relatively good since it produced higher R^2 values than any of the standardised SNQs for *sound types* S1–S3. The values were also reasonably high for *sound types* S4–S5. Thus, the reference spectrum serves the original purpose of being better than any of the standardised SNQs.

Table 8 shows that the shape of the optimal reference spectrum L_{Opt} including all *sound types* is rather varying within the frequency range. However, in the calculation of a SNQ based on this reference spectrum, the varying spectrum is not a problem. In the optimization process, the maximum level difference between adjacent frequency bands of the reference spectrum was limited to 5 dB to avoid too uneven reference spectra. By reducing the limit down from 5 dB, a smoother reference spectrum could have been achieved. The correlation might then have been weaker than with the presented reference spectrum. The varying shape of the reference spectrum L_{Opt} depends partly on *sound type* S5 (chair moving). Without that the spectrum shape might be less varying. This sound type, however, was considered so important that it was included in the analysis.

The optimisation of new SNQs was based on a single psychoacoustic experiment. It is possible that different results would be obtained for different *sound types* or different floor types. The optimisation did not involve e.g. wooden constructions so that the results presented here may be less valid for wooden floors than for concrete floors. Therefore, it is strongly recommended that similar independent studies are conducted to confirm or question the findings and clarify the remaining questions dealing with wooden floors, for example.

4.5 Measurement uncertainty

4.5.1 Normalised impact sound pressure levels

On the basis of earlier studies (Bodlund 1976; Olesen 1992; Göransson 1993; Simmons 2005), it can be expected that the standard deviations of the simulated values of normalised impact SPLs $L'_{n,sim,j}$ increase as the frequency decreases. The increase begins at the centre frequency of 400 Hz. The maximum value of the average is 1.0 dB at 63 Hz. Compared with the average standard deviation at 100 Hz, the increase is 0.15 dB. In single field measurements, the maxima of standard deviations occurred at centre frequency bands 50, 63, 80 and 100 Hz. The maximum standard deviations were 1.6, 1.8, 1.5 and 1.7 dB, correspondingly. At the frequency range below 100 Hz, no rapid increase of standard deviation cannot be seen in the standard deviations of the simulated values of $L'_{n,sim,j}$. Corresponding result could also be expected on the theoretical basis presented by Lubman (1974).

The averages of standard deviations of simulated normalised impact SPLs $L'_{n,sim,j}$ were around 1 dB at the lowest centre frequency bands and 0.5 dB or less at frequency bands higher than 250 Hz. The standard deviations of SNQs are in most cases smaller than the standard deviations of simulated normalised impact SPLs $L'_{n,sim,j}$.

The largest standard deviations of simulated SNQs are 0.8 dB. The standard deviations of D1 ($L'_{n,w}$), D2 ($L'_{n,w} + C_I$) and D4 (R_{impact}) tend to be larger for floor types D and E than for A, B and C. This can be interpreted so that the standard deviations of D_i do not depend on the measured frequency range only, but also on the spectrum of of L'_n or R_i.

Rating the floor by single-number quantity $L'_{n,w} + C_{I,50\text{-}2500}$ or R_{impact} may change the rating of the floor more than 10 dB compared with $L'_{n,w}$. The change in the measurement uncertainty at the enlarged frequency range remains evidently much lower than the change in the rating of floors. From this point of view, it is not justified to put the increased measurement uncertainty of the standardised SNQs at enlarged frequency range under question. This result differs from the conclusions of a study dealing with measurement uncertainty evaluation of the SNQs for airborne sound insulation (Hongisto *et al.* 2012).

4.5.2 Frequency weighting

In the case of floors F6…F9, the positions of the reference curves are determined by the values of L'_n at 1/3-octave bands below 200 Hz. It is known on an empirical and theoretical basis that standard deviations of normalised impact SPLs $L'_{n,w}$ measured at 1/3-octave bands rise at lower frequencies. The results of **Publication IV** have also confirmed that the spectrum of L'_n affects the measurement uncertainty of SNQ.

The differences between the standard deviations D_i cannot, however, be explained by the earlier results only. On the basis of the shapes of the reference curves, impact sound spectra of the floors and calculated SNQs, it can be stated that the shape of the reference curve also significantly affects the uncertainty of the SNQs. The more the reference curve weights the low frequencies in the rating of floors, the larger the standard deviations of D_i become.

The standard deviations of Di are largest in the case of Hagberg's (2010) reference curve, which has the steepest slope at the frequency range below 100 Hz. In the case of floor F8, standard deviation of $D_{L'n,Hag}$ is nearly 0.9 dB larger than standard deviation of $D_{L'n,w}$ and $D_{L'n,Ger}$. The probability distributions are the flatter and standard deviation the larger the more the SNQ weights the low frequency range.

The difference between the weakest and the best ratings of the nine floors was 38.6 dB when rated with $L'_{n,w}$. The corresponding difference was only 10.7 dB, when rated with $L'_{n,Bod}$. The use of different SNQ's changes the rating of a floor and the ranking order of the floors as well. The changes in rating and ranking order of floors are much larger than the changes in measurement uncertainties when the low frequency range is taken into account, even when the rating method weights strictly the low frequency range. This means that the uncertainty questions at low frequencies are not necessarily as important as they have earlier thought to be (Rasmussen & Rindel 2010).

The bearing structure of the floors was in this study a concrete hollow core slab. The results are thus valid for concrete structures only. The effect of workmanship might be more significant in the case of wood structures as has been reported by Öqvist *et al.* (2012).

5 CONCLUSIONS

5.1 New single-number quantities

The SPLs generated by the tapping machine and real impact sounds were measured for nine floors having the same bearing concrete slab and different coverings. Eight different single-number-quantities were calculated based on the tapping machine excitation. Three noise ratings, equivalent A-weighted SPL, $L_{A,eq}$, maximum A-weighted SPL, $L_{A,F,max}$ and loudness level L_N, were determined for living impact sounds, which were walking with socks, walking with soft-heeled shoes, walking with hard-heeled shoes, moving a chair and bouncing a super ball.

The results indicated that walking with socks generates SPLs which at frequency bands below 100 Hz are higher than the SPLs generated by walking with hard-heeled or soft-heeled shoes. The results also confirm that compared with walking on other floor coverings, walking on light-weight floating floors may generate 5–15 dB higher SPLs below 100 Hz compared with other floor types. It can be suggested that impact sound insulation at low frequency range is not related to wooden floors only but also to concrete floors.

The noise ratings of walking with hard-heeled shoes correlated strongly with the SNQs based on the tapping machine. The correlation coefficients between the noise ratings of chair moving and SNQs were also strong. Walking with soft-heeled shoes correlated strongly with the SNQs only in the case of one walker of three. There was no statistically significant correlation between the noise ratings of walking with socks and the SNQs. That is, the SNQs ranked the floor structures in an inadequate way regarding the situation when the impact sound source is walking with socks.

The correlation analysis of the noise ratings and the SNQs for rating the impact sound insulation showed that there was a need for a psychoacoustic experiment where walking sounds generated by different footwear on concrete floors with different floor coverings were investigated. In a psychoacoustic experiment, statistically significant correlation between the SNQs and subjective ratings were detected in the case of three *sound types* out of five. Of the SNQs presented in ISO 717-2 (2013), the best indicators of subjective *loudness* and *annoyance* regarding walking with hard-heeled and soft-heeled shoes and chair moving were $L'_{n,w} + C_I$ and $L'_{n,w}$

+ $C_{I,50\text{-}2500}$ followed by three alternative SNQs presented in research literature. The differences between these five SNQs were small. However, the subjective rating of loudness and annoyance of walking with socks and super ball bouncing were either weakly correlated or not correlated with the SNQs. These sound types cannot be considered as uncommon living sounds. In other words, the present SNQs do not cover all sound types occurring in dwellings. The psychoacoustic experiment indicated that there is a need for the development of new SNQs of impact sound insulation which would correlate better with the subjective annoyance of general sound types.

New SNQs were developed by the means of mathematical optimisation. As a starting point for the formulation of the new SNQs it was required that they can be expressed as the sum of $L'_{n,w}$ or $L'_{nT,w}$ and a new spectrum adaptation term instead of C_I or $C_{I,50\text{-}2500}$. An optimised reference spectrum could be developed for each five *sound types*, each leading to a better correlation between the subjective judgement of the *annoyance* of the sounds and the single-number quantities than can be achieved by using any of the single-number quantities presented in the standard ISO 717-2 (2013). In addition, an optimised reference spectrum could be derived which explained the annoyance of all five *sound types* reasonably well ($R^2 = 0.93$) and better than any of the standardised single number quantities (e.g. $R^2 = 0.86$ for $L'_{n,w} + C_{I,50\text{-}2500}$).

5.2 Measurement uncertainty

It was shown that the measurement uncertainty of the SNQs depends on the impact sound spectrum of the floor type. The measurement uncertainty of 1/3-octave band values does not depend on the floor type, which means that the uncertainty of the single number quantities is connected with the impact SPLs that determine the value of the SNQs. The measurement uncertainties of both the 1/3-octave band values and the SNQs rise when the 1/3-octave bands 50, 63 and 80 Hz are included in the rating. This change, however, remains insignificant when compared with the change in floor rating.

Based on the laboratory measurements, it could also be shown that the shape of the reference curve and its frequency range have a remarkable effect on the uncertainty of the single-number quantities. The uncertainty of an SNQ thus depends both on the impact sound spectrum of the floor and on the shape and frequency range of the reference curve or reference spectrum. This means that uncertainty of an SNQ should be taken into account when possible alternative reference spectra or alternative reference curves will be developed. The measurement uncertainty at a low frequency range, however, does not become so large that it would prevent developing new reference curves that weight this frequency range more strictly then the present, standardised reference curves starting at 100 Hz.

5.3 Limitations and further work

According to the author's knowledge, this study was the first where single-number quantities for rating the impact sound insulation were derived on the basis of a psychoacoustic experiment. Even though the combination of a psychoacoustic laboratory experiment and mathematical optimization proved to be a useful tool for deriving single-number quantities, further similar work involving impact sound insulation of different floors is needed to confirm these findings.

This research concentrated on impact sound insulation of concrete floors. No lightweight structures like wooden intermediate floors were studied. As the impact sound insulation of wooden floors is a subject of scientific interest, mathematical optimization based on physical measurement results of impact sound insulation and a psychoacoustic laboratory experiment should be applied for wooden floors, too. This is important as the single-number quantities for judgment of the impact sound insulation should rather be universal than dependent on building materials used in the construction.

The psychoacoustic experiment was carried out in a laboratory having a constant background noise level. In an apartment, the perception of living impact sounds depends also on masking effect of background noise generated by HVAC installations. It is not known how the background noise with varying spectrum and sound pressure level effect on the experience of living impact sounds heard from neighbouring dwellings. This is a question that could be studied by organizing a psychoacoustic experiment with varying background noise.

On the basis of the results of this study, it can be suggested that walking on concrete floors covered with floating floors might be a noticeable source of low-frequency sound. However, this study concerned three floating floors. There is a broad scale of different floating floors on the market. A psychoacoustic experiment concerning the perception of living impact sounds from walking on a wide scale of different floating floors constructed both on concrete and wooden bearing structures might give useful information on the behaviour of floating floors, which could be utilized in development of these structures.

This study concentrated on development of new single-number quantities for rating the impact sound insulation. The limits for maximum allowable values of the new single-number quantities were not studied. This could be a topic of a future study concerning impact sound insulation.

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PUBLICATIONS

PUBLICATION
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Correlation between single number-quantities of impact sound insulation and noise ratings of walking on concrete floors

Mikko Kylliäinen, Jesse Lietzén, Ville Kovalainen & Valtteri Hongisto

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Authors:
Mikko Kylliäinen[1]
Jesse Lietzén[1]
Ville Kovalainen[1]
Valtteri Hongisto[2]

Affiliation:
[1] Tampere University of Technology, Department of Civil Engineering, P. O. Box 600, FI-33101 Tampere, Finland, tel. +358 40 849 0825, mikko.kylliainen@tut.fi
[2] Finnish Institute of Occupational Health, Indoor Environment Laboratory, Lemminkäisenkatu 14–18 B, 20520 Turku, Finland, valtteri.hongisto@ttl.fi

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Abstract
The aim of this study was to investigate whether the low frequency range of 50–100 Hz should be taken into account when impact sound insulation of concrete floors is determined. Another aim was to determine the correlation between objective noise ratings of walking noise and single-number-quantities (SNQs) based on sound spectra produced by the tapping machine. Impact sound pressure levels (SPL) generated by the tapping machine on an uncovered concrete slab and on the same slab covered with eight floor coverings were measured. For each of these nine structures, eight various SNQs were calculated. The SPLs generated by three walkers wearing socks, soft-heeled shoes and hard-heeled shoes were also measured as well as noise generated by chair moving and super ball bouncing. These sounds were objectively evaluated by three noise ratings: equivalent A-weighted SPL, $L_{A,eq}$, maximum A-weighted SPL, $L_{A,F,max}$, and loudness level, $L_{N.}$ At frequency bands below 100 Hz, walking with socks generated higher linear SPLs than those generated by walking with hard-heeled or soft-heeled shoes. Walking on floating floors installed on the concrete slab also generated high SPLs in the low frequency range. The noise ratings of walking with hard-heeled shoes and chair moving correlated strongly with the SNQs based on the tapping machine. However, no statistically significant correlation between the noise ratings of walking with socks and the SNQs was detected. This indicates that there is a need for a new objective SNQ in order to improve the correlation between the different walking sounds and objective rating of the concrete floors.

PACS: 43.55.-n

Keywords: building acoustics, impact sound insulation

1. Introduction

Requirements for a single-number-quantity (SNQ) describing impact sound insulation of floors in residential dwellings were defined in 1949 by Gösele [1]. His definition required that the SNQ should be based on an objective sound source and measurement equipment, but the results determined by the objective method should correspond as well as possible to the occupants' subjective experience of sounds related to walking on a floor. Furthermore, the measurement result of two floors should be similar if these floors were subjectively judged similar.

The first attempts to connect impact sound insulation of floors to subjective experience of transmitted impact sounds were done in the late 1950's [2–3], but research dealing with this question became more active after the international standardization of the tapping machine in 1960. The tapping machine was criticized soon after its standardization, because its loudness and sound spectra were considered to differ too much from the sound generated by walking [4–6]. It was also shown that no such a constant or formula can be derived that could in all situations be used to calculate the walking spectrum from the spectrum generated by the tapping machine [7].

After the standardization of the tapping machine, there have been several ways of approaching the relation of the subjective experience of impact sounds and objective SNQs of impact sound insulation. A first approach is replacing the standard tapping machine with a new sound source such as a rubber ball [8, 9]. Even though the international standards [10, 11] now allow the use of the rubber ball in laboratory measurements, it seems obvious that the unmodified standard tapping machine will still remain as the official impact sound source in Europe [12].

A second approach in finding the correlation between the objective SNQs of impact sound insulation and the subjective rating of walking sounds is to carry out listening experiments where recorded walking sounds are evaluated by a group of test persons [13–18]. A third approach is trying to find a correlation between objective SNQs and subjective evaluation based on questionnaires or interviews *in situ* [19–21]. Finally, a fourth approach is finding the correlation of the objective SNQs with noise ratings like the equivalent A-weighted sound pressure levels (SPL), $L_{A,eq}$, the maximum A-weighted SPL $L_{A,F,max}$, loudness or loudness level [22–26]. In references 13–17, a detailed description of the tested floors was not always included or the derivation of the noise ratings describing the walking sounds has not been thoroughly reported. Due to the lack of information on the sound spectra generated by walking on different floors, the reasons for the subjective ranking of the floors are not necessarily clear.

Impact sounds in residential dwellings cover several sound sources like moving the furniture, playing children, falling objects and walking. The impact sound spectrum excited by walking depends on several factors including the floor structure, the personal walking style and the footwear. In most of the previous studies, the impact sounds have been produced by a test person using shoes. In many cases, the test persons have worn hard heeled shoes as they have been considered to be the worst case [6, 7, 15, 22–24, 27–29]. In many countries, for example in Finland and in other Nordic countries, occupants do not usually wear shoes at home. In some recent publications dealing with wooden floor structures, there are also results achieved by using impact sound spectra from walking with socks [13, 14, 18, 21].

An important question related to the sound spectrum of impact sounds and the rating of impact sound insulation is the frequency range to be measured. Enlarging the lower limiting frequency band from 100 Hz to 50 Hz was considered already in the 1960's on the basis of studies dealing with concrete structures [6]. In later studies, the necessity of doing measurements below 100 Hz has concerned especially wooden floors [13, 14, 19, 24, 25]. The recent European research has also focused on the impact sound insulation of wooden floors and on low-frequency sounds generated by walking on them [18, 21, 30]. Wooden floors often include a floating floor which improves impact sound insulation significantly at high frequencies.

There are some results implicating that the consideration of impact SPLs below 100 Hz should be done also in the case of concrete floors. Such reported cases include walking on floating floors [7, 22, 31–33], constructed on the bearing concrete slab. Currently, a vast majority of European dwellings are constructed of concrete or other massive structures [34]. The volume of concrete structures in housing stock and earlier reported flaws in low-frequency impact sound insulation of concrete floors [7, 22, 31–33] make them a relevant research topic, especially because of the lack of knowledge related to the sound generated by walking with different footwear on a wide scale of present-day floor coverings and floating floors installed on concrete floors.

The aim of this study was to investigate whether the low frequency range 50–100 Hz should be taken into account when impact sound insulation of concrete floors is determined. Another aim was to define the correlation between objective noise ratings of walking and single-number-quantities (SNQs) of impact sound insulation based on the tapping machine. The study was carried out using a wide range of floor coverings in order to cover the most typical impact sound insulation spectra found in dwellings.

2. Materials and methods

2.1 Testing laboratory

The impact sound measurements were carried out at Upofloor laboratory in Nokia, Finland, where the bearing structure of the floor separating the vertically adjacent source and receiving rooms is a 265 mm thick concrete hollow core slab (400 kg/m^2). It was the most usual prefabricated slab type in Finnish apartment buildings during the 1980's and 1990's [35]. The width and length of the source room were 4,4 m and 6,0 m. The floor area of the receiving room beneath the source room was 24 m^2 and its volume was 60 m^3. There were no diffusors in the receiving room. Measured reverberation times of the receiving room (table 1) corresponded well with those of typical furnished rooms in Finnish dwellings [36]. Therefore, the sound spectra measured in the receiving room correspond well with the typical spectra in residential dwellings.

Table 1. Measured reverberation times in the receiving room at octave bands.

Octave band	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Reverberation time	1,3 s	0,4 s	0,4 s	0,4 s	0,4 s	0,5 s	0,4 s

In the laboratory, all the floor coverings were installed in the same place on the slab. The size of the floor covering was 3,0 x 4,0 m^2 (figure 1). The floor coverings were installed as carefully as possible in order to avoid the effects of workmanship on the deviation of measured SPLs.

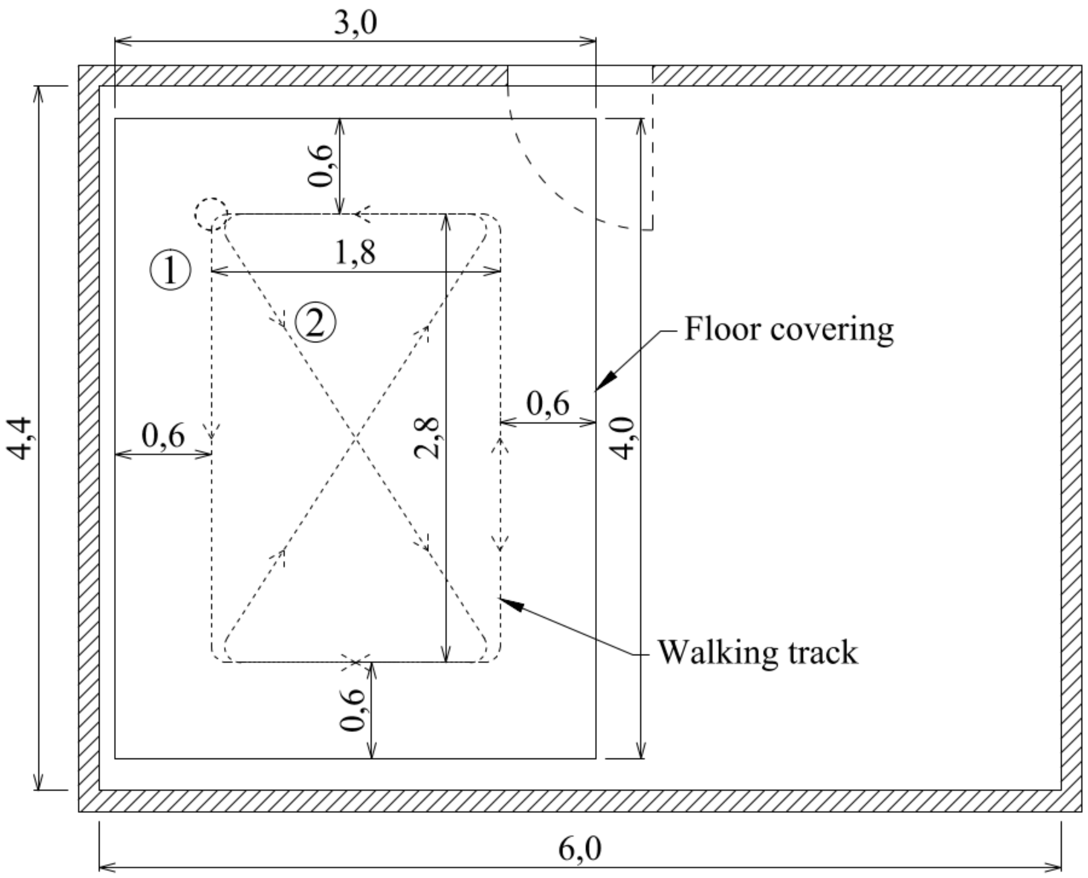

Figure 1. Placement of the floor coverings and walking track in the source room of the laboratory.

2.2 Measured structures

The study was carried out using a wide range of floor coverings in order to cover the typical impact sound insulation spectra found in dwellings. Eight different floor coverings on the bearing slab were used (table 2). One measurement was also carried out without floor covering (F1). In a laboratory test series, when floor coverings have to be quickly changeable, it was not possible to use cast concrete or cement screed as floating layers of floating floors. Thus, floating layers were constructed of varying number of plasterboards and mineral wool layers with varying thicknesses in order to compose structures having different resonance frequencies at the frequency range below

100 Hz. Cushion vinyls and multi-layer parquets were used in order to achieve resonance frequency around 400–500 Hz. Also very hard cushion vinyl and very soft floor-to-floor carpet were used.

The weighted reductions in impact sound pressure level ΔL_w shown in table 2 were defined according to standard ISO 717-2 [37]. The dynamic stiffnesses s' of the insulation layers of the floating floors were measured according to standard ISO 9052-1 [38].

Table 2. Structural layers of the floor coverings denoted with letter F and a number 1–9.

Denotation	Structural layers of floor covering
F1	No covering
F2	Cushion vinyl, ΔL_w = 2 dB
F3	Cushion vinyl, ΔL_w = 21 dB
F4	Multilayer parquet 14 mm Soft underlay, ΔL_w = 20 dB
F5	Wall-to-wall carpet, ΔL_w = 21 dB
F6	Wall-to-wall carpet, ΔL_w = 37 dB
F7	Multilayer parquet 14 mm Soft underlay 2 x plasterboard 15 mm (30 kg/m^2) Mineral wool 13 mm, s' = 16,1 MN/m^3
F8	Multilayer parquet 14 mm Soft underlay 2 x plasterboard 15 mm (30 kg/m^2) Mineral wool 50 mm, s' = 11,5 MN/m^3
F9	Multilayer parquet 14 mm Soft underlay 4 x plasterboard 15 mm (60 kg/m^2) Mineral wool 50 mm s' = 11,5 MN/m^3

2.3 Single-number-quantities based on tapping machine

The measurements were done according to the field measurement standard ISO 140-7 [39] as the laboratory constructed in the 1980s did not fulfil the present requirements for the laboratories in all respects. There were four fixed tapping machine positions on the floor of the source room and the sound generated by the tapping machine was measured in four fixed microphone positions. Two corner positions for loudspeakers were used in the reverberation time measurements. The number of the fixed microphone positions was four per each loudspeaker position. In each position, two decays were measured. The normalized impact SPLs L'_n were calculated from the spatial averages of 16 impact SPL measurements and 16 reverberation time measurements.

The standardized SNQs were determined on the basis of the normalized impact sound pressure levels L'_{n}. The weighted normalized impact sound pressure levels $L'_{n,w}$ as well as the sum of $L'_{n,w}$ and spectrum adaptation terms C_{I} and $C_{I,50-2500}$ were calculated according to the standard ISO 717-2 [37].

In addition to the standardized SNQs, four suggested SNQs were calculated. Reference curves defined by Fasold [6], Gerretsen [28], Bodlund [19] and Hagberg [20] were used (figure 2). The SNQs are denoted by $L'_{n,Fas}$, $L'_{n,Ger}$, $L'_{n,Bod}$ and $L'_{n,Hag}$, respectively. As the SNQ presented by Fasold can be calculated from the measured L'_{n} at frequency range 100–3150 Hz or 50–3150 Hz, the lower limit of the frequency range is indicated for $L'_{n,Fas}$. In the calculation of each SNQ, the maximum allowable sum of unfavourable deviations from the reference curve has been 32 dB, as it was shown in 1985 that changing the evaluation rule by varying the sum of unfavourable deviations does not have a significant effect on the rating of the floors [19]. In order to achieve a more precise understanding of the correlation between the SNQs based on the tapping machine and the SNQs based on walking, the principles of reference [40] were followed and all SNQs were defined by moving the reference curve in steps of 0,1 dB.

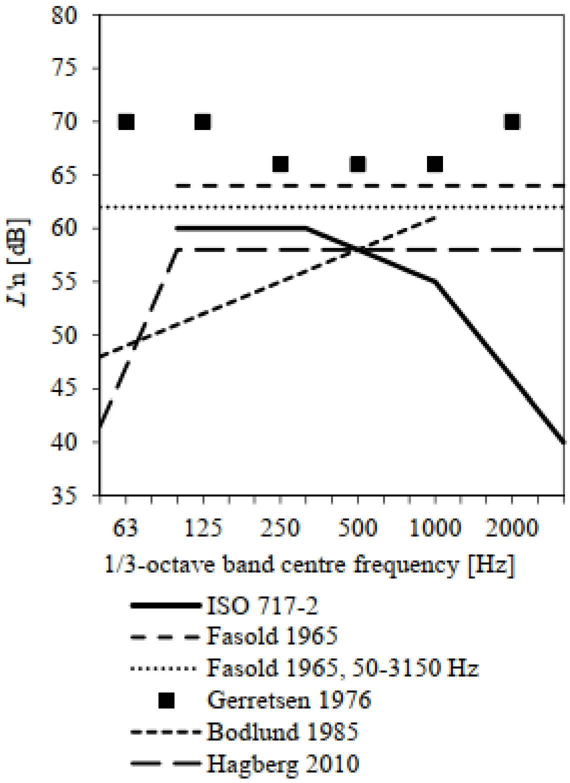

Figure 2. The reference curves used in calculation of the standardized (ISO 717-2) and the suggested SNQs, shown by the other curves.

2.4 Noise rating of impact sounds

Each of three male walkers W1, W2 and W3 (table 3) wore socks, soft-heeled shoes and hard-heeled shoes. The same footwear was used through the test series. Each walker walked along a rectangular and an hourglass-shaped track on each floor covering (figure 1). The SPLs were recorded in the receiving room at two microphone positions as a function of time with time weighting FAST. The measurement and walking duration was 40 seconds in all cases. The measured frequency range was 20–20000 Hz. All walkings were performed twice.

Before calculating the noise ratings, the measured walking SPLs were background-noise corrected. Equivalent level of A-weighted background noise $L_{A,eq}$ was 17–18 dB. At 50 Hz, the background noise level was 20–25 dB which was well below the measured impact sounds. At highest frequency range, the measured sound consisted in many cases of background noise only. The situation was such especially in the case of walking with socks and walking on floating floors and on softer wall-to-wall carpet.

Table 3. Description of the walkers. The shoe sizes correspond to the European measures.

Walker	Age	Mass	Height	Shoe size
W1	22	86 kg	188 cm	46
W2	40	125 kg	191 cm	44
W3	23	91 kg	183 cm	42

Background-noise corrected time-varying walking sounds were objectively rated by three noise ratings: equivalent A-weighted SPL, $L_{A,eq}$, calculated over the 40 s measurement period, maximum A-weighted SPL, $L_{A,F,max}$, and loudness level, L_N. Similar noise ratings have been used in evaluation of walking sounds [22–26], even though the derivation of the rating from walking sounds may differ from the procedure presented here.

It is usually expected that the experienced loudness of a time-varying sound is determined by the loudest momentary spectrum [41–43]. However, both $L_{A,F,max}$ and L_N vary frequently over relatively long time as each step generates a sound slightly different from other steps (figure 3). For this reason, the momentary maximum spectra were selected from the time-varying sound pressure by calculating both $L_{A,F}(t)$ and $L_N(t)$ of the walking sound as functions of time. Depending on the walker, typical number of maxima was 50–60 per each recording.

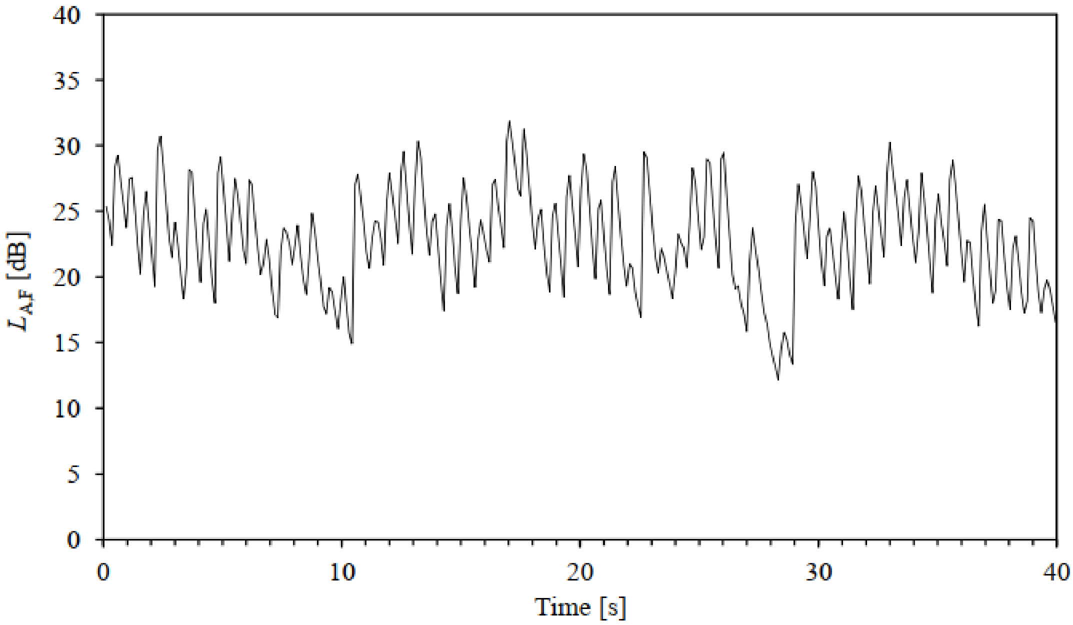

Figure 3. An example of the variation of the $L_{A,F}$ generated by walker W1 wearing socks walking on floor F4. Each peak represents a momentary maximum (an individual step).

Plotting the spectra of all momentary maxima of two repeated walks recorded in two measurement positions resulted in a sample of spectra based on either maximum A-weighted SPLs (figure 4) or loudness levels. The sample size consisted typically of 200–250 momentary maxima. From these maxima, the typical spectra of each walking were calculated as energetic averages of the sample of the spectra. The results, i.e., $L_{A,F,max}$ and L_N, were then calculated from these energetic averages. The calculation of loudness level $L_N(t)$ was carried out according to standard ANSI S3.4-2007 [44], which includes the loudness model by Moore and Glasberg [45–46] being the newest standardized model. The loudness levels were calculated on the basis of the SPLs at 1/3-octave bands in frequency range from 50 Hz to 16000 Hz according to the standard.

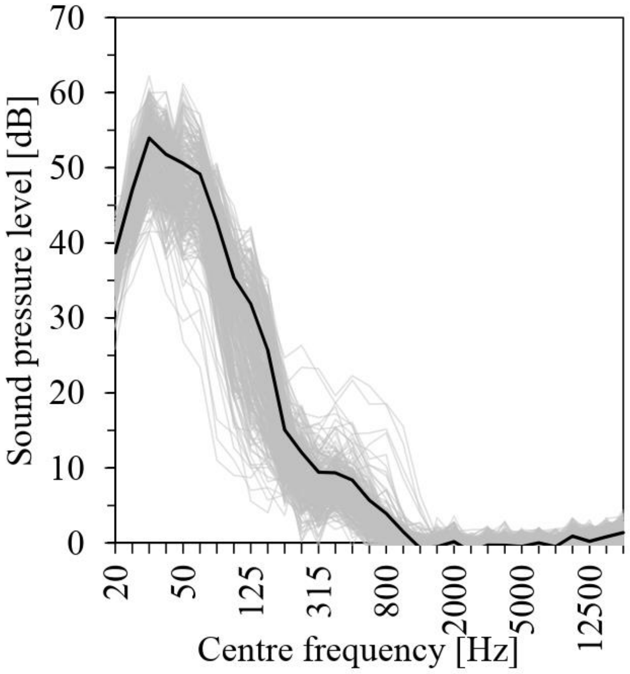

Figure 4. Examples of the spectra of momentary maxima of $L_{A,F}(t)$ described in figure 3. The energetic average $L_{A,F,max}$ representing a typical step sound is shown with black line.

There are several sources of impact sounds in dwellings like jumping, moving the furniture, falling objects or children playing. In addition to walking, two other impact sounds were studied here. The first represented one possible sound spectra caused by playing children: a so called superball (weight 45 g) was thrown towards the floor at the center point of the floor covering. The bouncing was repeated so that the ball was turned back towards the floor from the same height (1 meter). Also the sound produced by moving a wooden chair was measured. The sound was generated as follows: first, a walker pulled the chair away from a table, then the person moved to the front of the chair and moved it towards the table, sat down on the chair, stood up, pushed the chair away from the table and finally pushed the chair back under the table. In both cases, the measurement procedure was similar to the measurement of walking sounds. Floor F6 (wall-to-wall carpet for dwellings) was so soft that moving the chair in the way described before was impossible, and thus it was not measured.

With floors F4 and F8 three more impact sound sources were tested: vacuum cleaning, falling of knife from a table and female walker. The results from measurements of these sound sources are not included here for following reasons: vacuum cleaning appeared to be the most quiet of all sounds, and, thus, is obviously not a significant sound source; falling knife generated sound spectra similar to chair moving; the shape of the spectra generated by the female walker was similar to the male walkers, and loudness of the female walker was inside the range of the sounds generated by the male walkers. These test were carried out in order to study whether these three sound sources generate spectra significantly different from the other impact sound sources described earlier, but that was not the case.

2.5 Correlation between single-number quantities

The correlation between the noise ratings and the different SNQs based on the tapping machine (see table 7) were studied by calculating the squared Pearson product-moment correlation coefficients, i.e., the coefficients of determination r^2 for all combinations of sound sources, footwear and floors.

2.6 Repeatability of walking sounds

In order to ensure that the walking of each walker remained similar during the test period of one month, walking with soft-heeled shoes on the first test floor F1 was repeated by all three walkers on six days. On each day, the walking was repeated twice so that there was an interval of 5–10 minutes between the first and the second walk. The procedure described in chapter 2.3 was followed in the measurements. The mean value (M), standard deviation (STD) and maximum deviation (MD) of $L_{A,eq}$ of the 12 walks are shown in table 4.

Table 4. Mean value, standard deviation and maximum deviation of $L_{A,eq}$ [dB] of the repeated walkings on floor F1 by all three walkers wearing soft-heeled shoes.

Walker	M	STD	MD
W1	21,4	0,5	1,3
W2	15,0	0,4	1,3
W3	19,4	0,6	1,0

3. Results

3.1 The tapping machine

The normalized impact SPLs generated by the tapping machine on the nine floors are shown in figure 5. The SNQs calculated from them are given in table 5. The range of investigated impact sound pressure levels cover well the typical range found in buildings.

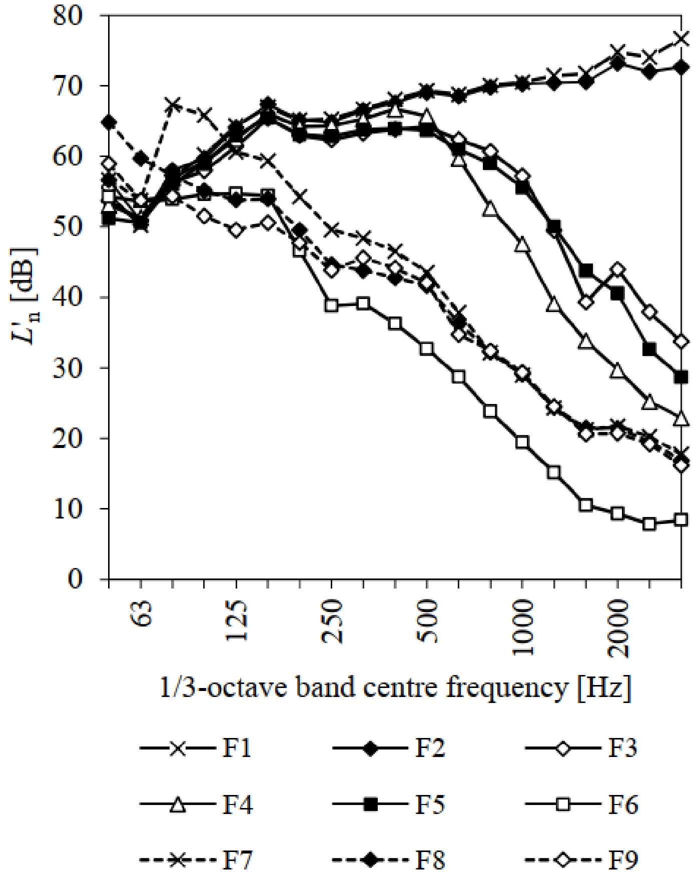

Figure 5. Normalized impact SPLs L'_n produced by the tapping machine placed on the nine floors.

Table 5. The standardized and suggested SNQs [dB] of the nine floors F1…F9 based on the tapping machine.

SNQ	F1	F2	F3	F4	F5	F6	F7	F8	F9
$L'_{n,w}$	79,9	77,7	58,7	59,1	58,5	42,7	50,1	43,2	41,3
$L'_{n,w} + C_I$	66,7	65,8	58,0	59,0	58,0	44,7	53,0	45,0	42,1
$L'_{n,w} + C_{I,50\text{-}2500}$	66,7	65,8	58,1	59,1	58,1	47,3	55,9	52,4	47,6
$L'_{n,Fas}$	68,4	67,3	59,4	60,4	59,4	44,7	52,1	45,2	43,0
$L'_{n,Fas,50}$	68,4	67,3	59,4	60,4	59,4	49,0	55,6	52,2	47,8
$L'_{n,Ger}$	66,4	65,6	58,4	59,8	58,6	41,9	50,3	43,6	41,5
$L'_{n,Bod}$	66,0	65,9	62,6	63,9	62,8	56,5	62,8	59,8	55,3
$L'_{n,Hag}$	68,7	67,8	60,7	61,8	60,5	54,5	61,2	61,0	56,1

3.2 Noise ratings of walking and other impact sound sources

The mean spectra of walking based on the energetic averages of the momentary maxima of the time-varying $L_{AF,max}$ are shown in figure 6. Similar curves could be drawn for $L_{A,eq}$ and for the momentary maxima of the time-varying loudness level L_N. These noise ratings based on these curves are given in table 6.

The noise ratings of the superball bouncing and the chair moving are also given in table 6. The corresponding energetic averages of momentary maxima of time-varying A-weighted SPL are shown in figure 7.

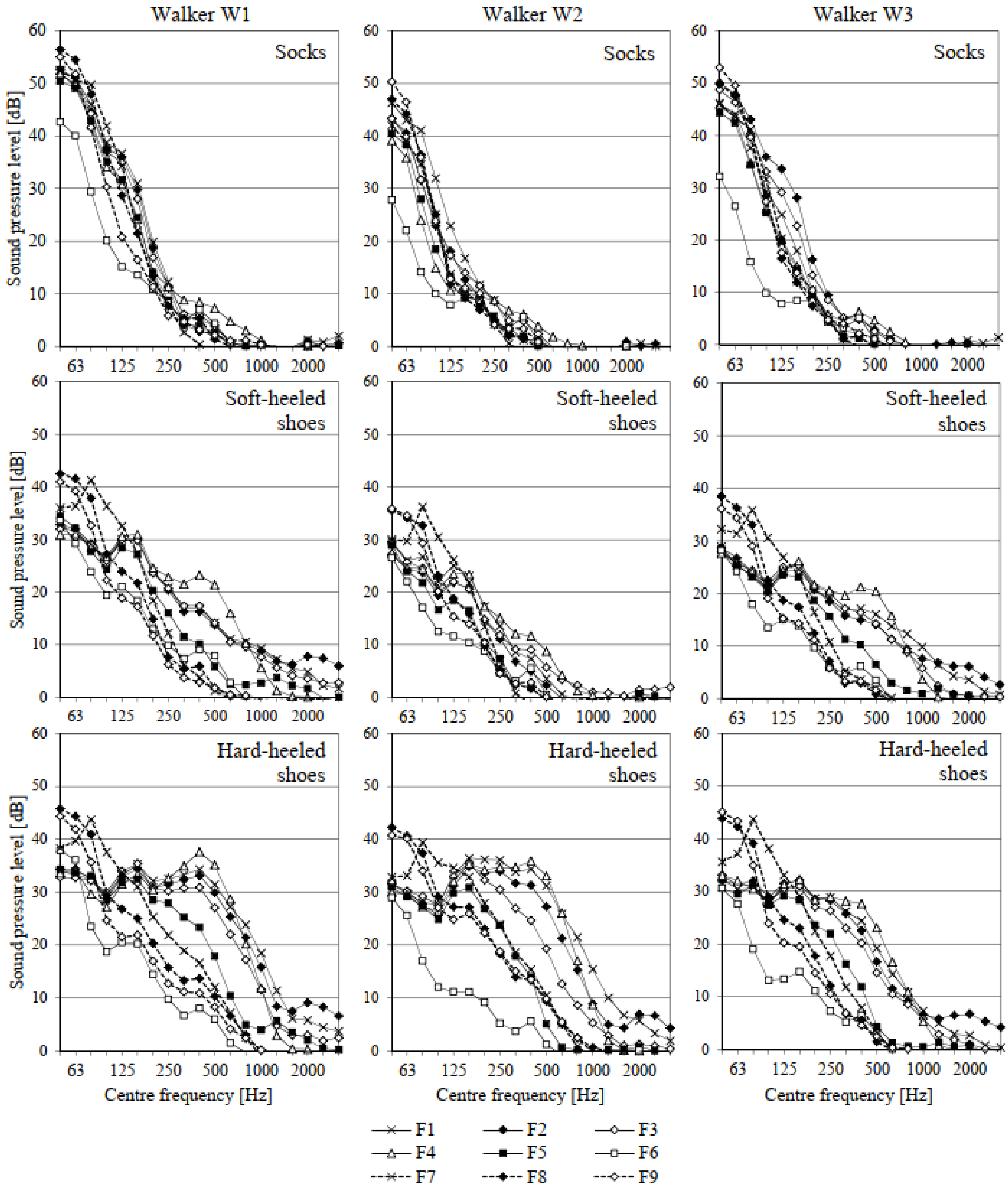

Figure 6. Energetic averages of walking sound spectra based on momentary maxima of $L_{A,F}(t)$ during 40 s.

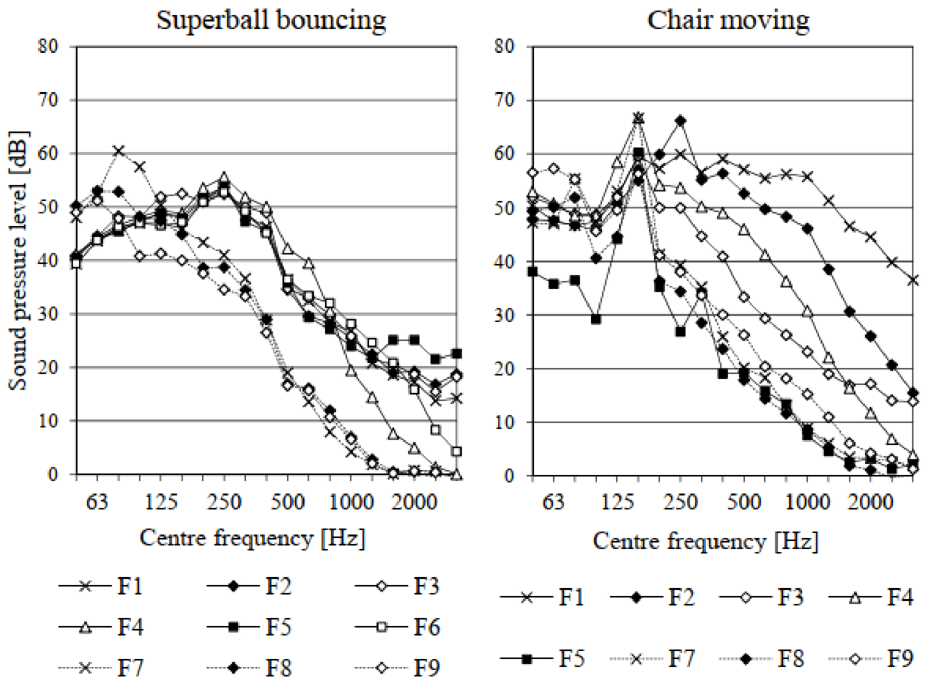

Figure 7. Energetic averages of sound spectra of ball bouncing and chair moving based on momentary maxima of $L_{A,F}$(t) during 40 s.

Table 6. Noise ratings determined for the various impact sound sources for the nine floors F1…F9.

Walker	SNQ	F1	F2	F3	F4	F5	F6	F7	F8	F9
W1, socks	$L_{A,eq}$ [dB]	27,8	27,7	26,6	26,1	25,6	18,9	28,5	30,1	27,7
	$L_{A,F,max}$ [dB]	30,6	30,2	29,3	28,5	28,1	21,1	31,4	32,6	30,2
	L_N [phon]	31,3	30,3	28,4	27,3	26,4	15,8	29,4	29,5	25,3
W2, socks	$L_{A,eq}$ [dB]	18,1	18,1	18,0	16,0	16,4	12,7	17,3	20,8	23,3
	$L_{A,F,max}$ [dB]	20,4	20,4	20,4	17,6	18,4	13,4	19,6	23,3	25,8
	L_N [phon]	16,0	16,8	15,5	13,9	13,7	13,1	14,3	17,5	19,4
W3, socks	$L_{A,eq}$ [dB]	21,3	25,1	23,6	20,4	19,7	13,8	21,5	23,6	25,7
	$L_{A,F,max}$ [dB]	23,6	27,8	25,9	22,8	21,9	15,1	24,0	26,0	28,2
	L_N [phon]	21,5	27,2	23,9	17,8	17,1	13,1	19,6	20,6	22,3
W1, soft-heeled shoes	$L_{A,eq}$ [dB]	21,3	21,2	20,9	22,7	19,4	16,4	21,3	20,5	20,2
	$L_{A,F,max}$ [dB]	23,7	23,8	23,4	25,8	21,1	17,7	24,0	22,3	21,4
	L_N [phon]	32,7	34,4	32,2	35,0	23,8	17,2	23,8	19,5	16,6
W2, soft-heeled shoes	$L_{A,eq}$ [dB]	14,6	13,5	14,4	15,3	12,7	12,1	15,8	14,9	14,7
	$L_{A,F,max}$ [dB]	16,9	15,3	16,5	17,5	13,7	12,7	18,7	16,4	15,9
	L_N [phon]	17,4	14,9	19,3	20,3	13,3	12,8	17,0	13,8	12,3
W3, soft-heeled shoes	$L_{A,eq}$ [dB]	19,0	18,3	18,5	20,1	15,9	13,1	17,4	16,4	16,2
	$L_{A,F,max}$ [dB]	21,9	21,2	21,2	23,4	17,8	13,9	19,5	17,9	17,4
	L_N [phon]	30,9	30,4	28,4	31,6	20,1	13,2	18,6	14,6	12,8
W1, hard-heeled shoes	$L_{A,eq}$ [dB]	31,0	29,9	27,9	32,9	23,9	17,9	23,9	23,0	21,8
	$L_{A,F,max}$ [dB]	35,2	33,9	32,0	37,2	27,2	19,3	26,8	25,0	23,4
	L_N [phon]	49,7	48,4	44,6	49,0	36,0	17,3	31,7	27,0	23,6
W2, hard-heeled shoes	$L_{A,eq}$ [dB]	30,7	27,9	24,5	31,1	19,1	13,0	21,8	20,2	20,0
	$L_{A,F,max}$ [dB]	35,6	32,8	29,0	36,1	23,0	13,8	25,9	22,7	22,0

	L_N [phon]	49,3	45,5	38,7	47,9	27,3	13,0	31,2	25,9	25,4
W3, hard-heeled shoes	$L_{A,eq}$ [dB]	23,9	23,4	22,2	25,3	19,0	13,9	22,6	20,8	21,5
	$L_{A,F,max}$ [dB]	27,4	27,0	25,2	28,9	21,7	14,9	25,6	22,7	23,1
	L_N [phon]	37,5	38,0	33,5	39,1	25,2	13,5	27,0	21,0	19,6
Superball bouncing	$L_{A,eq}$ [dB]	42,5	42,2	43,1	44,8	42,4	42,6	37,9	33,2	29,0
	$L_{A,F,max}$ [dB]	49,0	49,2	50,0	52,0	48,9	48,8	43,6	39,0	35,1
	L_N [phon]	64,2	65,3	66,5	64,7	66,2	63,7	52,6	49,3	45,3
Chair moving	$L_{A,eq}$ [dB]	59,8	55,3	44,5	52,4	42,8	-	49,3	40,5	40,3
	$L_{A,F,max}$ [dB]	63,1	60,6	49,1	55,7	47,0	-	53,5	44,2	44,6
	L_N [phon]	82,5	76,3	63,6	69,0	51,3	-	58,1	49,6	54,6

3.3 Correlation between noise ratings and SNQs based on the tapping machine

The calculated coefficients of determination r^2 between the noise ratings (table 6) and the SNQs based on the tapping machine and the reference curves (table 5) are given in table 7. The sample size was 9 which means that r^2 values exceeding 0,34 have a significance level of $p < 0{,}05$ and r^2 values exceeding 0,56 have a significance level of $p < 0{,}01$.

Table 7. Coefficients of determination r^2 between the noise ratings and SNQs based on tapping machine. Values exceeding 0,34 are bolded and values exceeding 0,56 are additionally underlined.

Sound source	SNQ based on walking	SNQ based on tapping machine							
		$L'_{n,w}$	$L'_{n,w} + C_I$	$L'_{n,w} + C_{I,50\text{-}2500}$	$L'_{n,Fas}$	$L'_{n,Fas,50}$	$L'_{n,Ger}$	$L'_{n,Bod}$	$L'_{n,Hag}$
W1, socks	$L_{A,eq}$	0,05	0,04	0,14	0,04	0,08	0,05	0,14	0,28
	$L_{A,F,max}$	0,05	0,05	0,15	0,05	0,09	0,06	0,15	0,29
	L_N	0,33	**0,34**	**0,51**	0,33	**0,42**	**0,35**	**0,51**	**0,64**
W2, socks	$L_{A,eq}$	0,02	0,06	0,01	0,04	0,02	0,04	0,04	0,01
	$L_{A,F,max}$	0,01	0,03	0,00	0,02	0,01	0,02	0,01	0,02
	L_N	0,00	0,05	0,01	0,04	0,02	0,04	0,06	0,01
W3, socks	$L_{A,eq}$	0,04	0,02	0,07	0,03	0,04	0,03	0,04	0,15
	$L_{A,F,max}$	0,05	0,03	0,09	0,03	0,05	0,04	0,05	0,17
	L_N	0,26	0,18	0,27	0,19	0,23	0,19	0,17	**0,36**
W1, soft-heeled shoes	$L_{A,eq}$	0,22	0,28	**0,37**	0,28	0,31	0,31	**0,42**	**0,41**
	$L_{A,F,max}$	0,27	**0,37**	**0,45**	**0,36**	**0,38**	**0,39**	**0,52**	**0,45**
	L_N	**0,72**	**0,83**	**0,78**	**0,83**	**0,80**	**0,85**	**0,79**	**0,61**
W2, soft-heeled shoes	$L_{A,eq}$	0,00	0,00	0,02	0,00	0,00	0,00	0,04	0,06
	$L_{A,F,max}$	0,02	0,05	0,10	0,04	0,06	0,04	0,16	0,16
	L_N	0,19	0,33	0,29	0,32	0,29	**0,34**	**0,40**	0,19
W3, soft-heeled shoes	$L_{A,eq}$	**0,42**	**0,50**	**0,56**	**0,51**	**0,51**	**0,54**	**0,57**	**0,52**
	$L_{A,F,max}$	**0,49**	**0,59**	**0,63**	**0,59**	**0,59**	**0,63**	**0,65**	**0,56**
	L_N	**0,76**	**0,85**	**0,80**	**0,86**	**0,82**	**0,87**	**0,76**	**0,62**

W1, hard-heeled shoes	$L_{A,eq}$	**0,63**	**0,70**	**0,72**	**0,72**	**0,71**	**0,74**	**0,70**	**0,63**
	$L_{A,F,max}$	**0,66**	**0,75**	**0,76**	**0,76**	**0,75**	**0,79**	**0,74**	**0,64**
	L_N	**0,77**	**0,86**	**0,86**	**0,88**	**0,86**	**0,90**	**0,82**	**0,70**
W2, hard-heeled shoes	$L_{A,eq}$	**0,60**	**0,62**	**0,68**	**0,63**	**0,65**	**0,65**	**0,63**	**0,66**
	$L_{A,F,max}$	**0,63**	**0,68**	**0,73**	**0,68**	**0,70**	**0,71**	**0,70**	**0,69**
	L_N	**0,70**	**0,73**	**0,78**	**0,74**	**0,76**	**0,76**	**0,72**	**0,72**
W3, hard-heeled shoes	$L_{A,eq}$	0,30	**0,34**	**0,43**	**0,34**	**0,37**	**0,37**	**0,43**	**0,48**
	$L_{A,F,max}$	**0,39**	**0,45**	**0,54**	**0,45**	**0,47**	**0,48**	**0,54**	**0,55**
	L_N	**0,71**	**0,80**	**0,81**	**0,81**	**0,80**	**0,83**	**0,79**	**0,69**
Superball bouncing	$L_{A,eq}$	**0,35**	**0,50**	0,33	**0,49**	**0,40**	**0,48**	**0,41**	0,14
	$L_{A,F,max}$	**0,38**	**0,53**	**0,35**	**0,52**	**0,42**	**0,51**	**0,42**	0,15
	L_N	**0,42**	**0,52**	**0,35**	**0,53**	**0,43**	**0,53**	**0,36**	0,14
Chair moving	$L_{A,eq}$	**0,76**	**0,71**	**0,77**	**0,68**	**0,75**	**0,65**	**0,69**	**0,78**
	$L_{A,F,max}$	**0,79**	**0,74**	**0,80**	**0,71**	**0,77**	**0,67**	**0,70**	**0,80**
	L_N	**0,79**	**0,68**	**0,72**	**0,69**	**0,73**	**0,66**	**0,54**	**0,71**

4. Discussion

4.1 Sound spectra of walking on concrete floors

Walking with socks generated the highest SPLs below 200 Hz. Walking with hard-heeled or soft-heeled shoes also generated highest SPLs below 100 Hz, but hard-heeled shoes generated SPLs exceeding typical background noise levels of Finnish dwellings [47] at frequency bands from 200 Hz to 1000 Hz as well (figure 8). Below 100 Hz, the walking levels correspond to the levels measured by other researchers from walking on wooden floors [22, 24, 43]. This means that low-frequency walking sounds are not prevalent only with wooden floors but they are also present with concrete floors.

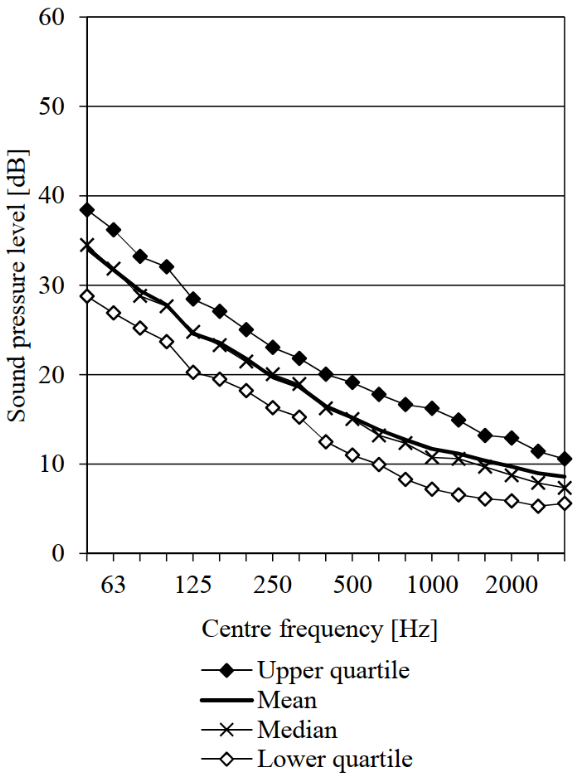

Figure 8. Linear background noise levels at 1/3-octave bands from HVAC systems in Finnish dwellings [47].

In most Finnish dwellings, the background SPLs generated by HVAC systems are below 38 dB at 50 Hz and below 32 dB at 100 Hz (fig. 8). Below 100 Hz, most of the measured SPLs generated by walking with socks on all floors were greater than the levels of background noise in typical Finnish dwellings. The excess was 10–15 dB regarding walking with socks on floating floors and 5–10 dB regarding walking with hard-heeled shoes on floating floors. This indicates that walking on concrete floors covered with floating floors is a noticeable source of low-frequency sound. The results presented here are in agreement with earlier results [7, 31, 32] even though the floor structures in the earlier studies have not been reported in detail.

It is noteworthy that walking with socks generated more sound below 100 Hz than walking with shoes. The level difference at the lowest frequency bands typically exceeded 10 dB except in the case of floor F6. It can thus be stated that walking with socks on concrete floors usually generates more sound in the low frequency range than walking with shoes. The result also indicates that walking with socks should be included in future walking tests.

4.2 Noise ratings versus single-number-quantities

In recent studies [13, 14, 18, 21], concrete floors have been excluded or they have been used only as reference material to wooden floors. All floors studied in our research can be considered massive as they had a concrete slab as a bearing structure. The standardized and the suggested SNQs rated the measured floors mostly on the basis of the sounds generated at mid-frequencies by the tapping machine. This frequency range is significant regarding walking with hard-heeled shoes. The values of noise ratings based on walking, however, were often determined by the walking sounds in the low frequency range.

The noise ratings $L_{A,eq}$, $L_{A,F,max}$ and L_N based on the same walker (table 6) wearing socks were pretty similarly independent of floor structure. The within-walker differences were below 7,3 dB, 7,4 dB and 6,8 phon for $L_{A,eq}$, $L_{A,F,max}$ and L_N, respectively, for floors F1–F9 if floor F6 is ignored. For instance, walker W1 generated a maximum sound level $L_{A,F,max}$ of around 28–30 dB in the case of floors F1–F5 and around 30–33 dB in the case of floating floors F7–F9. The range of loudness levels L_N were 26–31 phon and 25–30 phon, respectively. In the case of walkers W2 and W3 wearing socks there were results rating floating floors even louder than floors F1–F5.

In other words, the noise ratings based on walking with socks thus rate the floating floors equal to or louder than the bare concrete floor or floors with a light covering installed directly on the bearing concrete slab. The standardized and suggested SNQs based on the tapping machine, however, rate the best floating floor F9 about 10–38 dB better than the bare floor F1. As walking on floating floors generated more sound at low frequencies than walking on other floors, it can be concluded that low-frequency impact sound insulation of floors is not well included in the standardized [37] or suggested [6, 19, 20, 28] SNQs.

Floor F6 had clearly lower noise rating values than the other floors (table 6). When the standardized and suggested SNQs (table 5) of floors F6 and F9 are compared with each other, the difference of the same SNQ is 2,6 dB at highest and 0,3 dB at smallest. The SNQs thus rated these two floors almost equal. In the case of walking with socks, floor F6 had 6–12 dB lower $L_{A,eq}$, 9–13 dB lower $L_{A,F,max}$ and 6–10 phon lower L_N than floor F9 had. On the basis of real walking sounds, floor F6 would obviously be a better structure than the objectively best rated floating floor F9. Thus, the ranking order according to the SNQs based on the tapping machine is incorrect in this respect.

4.3 Correlation between noise ratings and SNQs based on the tapping machine

Table 7 describes the coefficients of determination r^2 between the SNQs based on the tapping machine and noise ratings of walking and other impact sound sources. The correlation coefficients might give an impression that the SNQs described in the present standard, i.e. $L'_{n,w}$, $L'_{n,w} + C_I$ or $L'_{n,w} + C_{I,50\text{-}2500}$, are satisfactory as correlation coefficients between them and the noise ratings of walking with hard-heeled shoes exceed 0,60. $L'_{n,w} + C_I$ or $L'_{n,w} + C_{I,50\text{-}2500}$ correlate also well with the walking of W3 with soft-heeled shoes. Widest range of statistically significant correlation coefficients was achieved using $L'_{n,w} + C_I$, $L'_{n,Fas}$ and $L'_{n,Ger}$ which correlated strongly with the superball bouncing in addition to the mentioned sound sources (figures 6 and 7).

The SNQs based on the tapping machine had, however, mainly a weak correlation with noise ratings of walking with socks. This result supports the earlier researchers' [7, 9, 22, 26, 31, 32] conclusions related to the significance of walking with socks and walking on concrete floors covered with floating floors. Most walkings of walkers W1 and W3 with soft-heeled shoes resulted in statistically significant correlation, but the walking of walker W2 did not. The probable explanation to this is that the sound pressure levels generated by W2 walking with soft-heeled shoes were lowest of the three walkers and W2 did not excite the resonance frequencies of floors F3, F4 and F5 like the other walkers did. This shows that in walking tests, more than one or two walkers are needed in order to avoid false conclusions. Nearly half of the correlation between the objective SNQs and the noise ratings of walking with soft-heeled shoes were, however, weak.

The results described in table 6 indicate that both the standardized SNQs defined in the present standard and the suggested SNQs do not correlate well with the noise ratings of walking with socks or soft-heeled shoes. This means that both standardized and suggested SNQs ignore the meaning of walking with socks as a sound source. There is an obvious need for a new SNQ which would take walking with socks better into account.

4.4 Limitations

The walkers could repeat their walking significantly well (table 4). It can thus be assumed that there were no such changes in walking that would have affected the measurement results of the actual walking tests and the differences between the nine floors. Furthermore, it is thus clear that the differences between the sound spectra shown in figure 6 depend on footwear and floor covering as well as on personal walking style. For example, the heaviest walker was not the loudest.

Three walkers were used in the generation of the walking sounds. It was justifiable to use three walkers instead of one or two, because there were differences between the walkers. Even though the SPLs generated by their walking varied, the shapes of the sound spectra of different walkers wearing the same type of footwear were quite similar. All walkers, however, were men between 22 and 40 years. It is possible that female walkers or other walkers might have generated different sound spectra, depending on their walking style.

The bearing floor structure was the same 265 mm thick hollow core slab in all measurements. This has been a typical structure in Finland from the 1970s to the end of the 1990s [35], but other European countries use a wide scale of different concrete slabs [34]. According to the standardized calculation method [48] of impact sound insulation, the higher mass of the slab reduces the impact SPLs generated by the tapping machine. The changing mass and stiffness of the slab also influences the critical frequency of the slab. Both tapping machine and walking on other floors than those studied here might generate sound spectra differing from the spectra presented here. In most countries, however, the thickness, and mass of concrete slabs are quite similar to the one studied here [34].

5. Conclusions

The SPLs generated by the tapping machine and real impact sounds were measured for nine floors having the same bearing concrete slab and different coverings. Eight different single-number-quantities were calculated based on the tapping machine excitation. Three noise ratings, equivalent A-weighted SPL, $L_{A,eq}$, maximum A-weighted SPL, $L_{A,F,max}$ and loudness level L_N, were determined for real impact sounds, which were walking with socks, walking with soft-heeled shoes, walking with hard-heeled shoes, moving a chair and bouncing a superball.

The results indicate that walking with socks generates SPLs which at frequency bands below 100 Hz are higher than the SPLs generated by walking with hard-heeled or soft-heeled shoes. The results also confirm that compared with walking on other floor coverings, walking on floating floors may generate 5–15 dB higher SPLs below 100 Hz. It can thus be stated that impact sound insulation at low frequency range is not related to light-weight structures only but also to concrete floors.

The noise ratings of walking with hard-heeled shoes correlated strongly with the SNQs based on the tapping machine. The correlation coefficients between the noise ratings of chair moving and SNQs based on tapping machine were also strong. Walking with soft-heeled shoes correlated strongly with the SNQs only in the case of one walker of three. However, there was no statistically significant correlation between the noise ratings of walking with socks and the SNQs. That is, the standardized SNQs ranked the floor structures in an inadequate way regarding the situation when the impact sound source is walking with socks. In the Nordic countries, walking with socks is the typical behaviour indoors at home.

There is an obvious need for listening experiments where walking sounds generated by different footwear on concrete floors with different floor coverings are investigated. A new objective SNQ based on the tapping machine or other standardized source as a stimulus is obviously also needed in order to improve the correlation between the subjective rating of different walking sounds and the objective rating of floors' impact sound insulation.

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PUBLICATION II

Subjective and objective rating of impact sound insulation of a concrete floor with various coverings

Mikko Kylliäinen, Valtteri Hongisto, David Oliva & Laura Rekola

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TITLE

Subjective and objective rating of impact sound insulation of a concrete floor with various coverings

AUTHORS

Mikko Kylliäinen[1]
Valtteri Hongisto[2]
David Oliva[2]
Laura Rekola[3]

AFFILIATIONS

[1] Tampere University of Technology, Department of Civil Engineering, P.O. Box 600, 33101 Tampere, Finland, mikko.kylliainen@tut.fi
[2] Finnish Institute of Occupational Health and Turku University of Applied Sciences, Indoor Environment, Lemminkäisenkatu 14-18 B, 20520 Turku, Finland, forename.surname@turkuamk.fi
[3] Finnish Institute of Occupational Health, Indoor Environment Laboratory, Lemminkäisenkatu 14–18 B, 20520 Turku, Finland, forename.surname@ttl.fi

CORRESPONDING AUTHOR

Mikko Kylliäinen, mikko.kylliainen@tut.fi

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SUMMARY

The aim of the study was to determine the associations between subjective rating of impact sounds directed to concrete floors and various single-number quantities (SNQ) of impact sound insulation. A psychoacoustic experiment was participated by 55 subjects in order to rate subjectively 44 sounds which were recordings of five actual impact sound sources directed to nine floor types. Eight objective SNQs were calculated. The squared Pearson correlation coefficients R^2 was determined between the objective SNQs and subjective annoyance or loudness. Statistically significant correlation between the SNQs and subjective ratings was detected for three sound types out of five. Of the SNQs presented in ISO 717-2, the best indicators of subjective loudness and annoyance regarding walking with hard-heeled and soft-heeled shoes and chair moving were $L'_{n,w} + C_I$ and $L'_{n,w} + C_{I,50\text{-}2500}$ followed by SNQs developed by Fasold, Gerretsen and Bodlund. $L'_{n,w}$ and the SNQ developed by Hagberg correlated weaker with the subjective loudness and annoyance of the mentioned three sound types. The subjective ratings of walking with socks and superball bouncing were weakly or not at all correlated with the SNQs. As walking with socks is probably the most common impact sound type in some countries including the Nordic countries, the present SNQs do not cover all important sound types occurring in dwellings. Thus, there is a need for the development of new SNQs which would correlate better with general sound types.

KEYWORDS

Impact sound insulation, annoyance, loudness, psychoacoustics, subjective assessment, single-number quantities

1. INTRODUCTION

1.1 Review of previous research

It has long been recognized that impact sound insulation should be expressed by such single-number quantities (SNQ) which correlate best with people's experience on impact sounds, such as walking. It is also obvious that a standardized sound source able to generate repeatable excitation is needed [1, 2]. Therefore, the formulation of a SNQ for impact sound insulation requires twofold research: physical measurements of impact sound levels generated by the sound sources and psychoacoustic experiments concerning walking and other usual impact sounds.

The first psychoacoustic experiments in order to connect measured impact sound insulation of floors with subjective experience of transmitted impact sounds were done in 1950s [3, 4]. During the last few decades, some psychoacoustic experiments have also been carried out. Many of the studies have aimed at some other objective [5, 6, 7, 8] rather than studying the association of the SNQs with the subjective experience of different impact sounds. For example, in the much referred work by Mortensen [9], the objective was to study how different impact sound spectra are subjectively evaluated in relation to loudness, disturbance and annoyance. The connection with the SNQs of impact sound insulation was not studied. There is only a rather small amount of research focusing on the question of relation of the SNQs to subjective rating of impact sounds.

Nilsson and Hammer [10, 11] studied how the SNQs for impact sound insulation and different noise and loudness ratings correlated with subjective evaluation of impact sounds. Impact sound insulation of eight floor structures were measured in the laboratory and the following SNQs were calculated: $L_{n,w}$ according to ISO 717-2 [12], $L_{n,w}$ with limitation of maximum deviation of 8 dB from the reference curve [13] and the SNQ suggested by Bodlund [14]. In addition to these, different noise and loudness ratings were defined. Two impact sound sources were used: female and male walker. Five of the eight floor structures were wooden floors and three were concrete floors. None of the floors had floor covering which means that neither the tapping machine spectra nor the walking spectra corresponded to the actual spectra of finished floors in buildings. Rather small number of subjects, only 13 persons, listened the sound samples via headphones. As the result of the study, the authors found that the SNQ defined by Bodlund [14] gave the best correlation with subjective evaluation of floors.

The structures in the studies by Gover et al. [15, 16] consisted of 19 different lightweight wooden floors. The floors were measured in the laboratory, and the SNQs according to standard ISO 717-2 [12] were calculated. In addition to tapping machine, modified tapping machine as well as rubber impact ball [17] and the Japanese bang machine with tire were used as sound sources in objective rating. For the psychoacoustic tests, four sound sources were recorded: three adult walkers without shoes and dropping of impact rubber ball from three heights. The psychoacoustic experiments were realized with only 12 subjects. As a conclusion, the authors state that the SNQs derived from the impact sound pressure levels generated by the modified tapping machine do not correlate with the subjective rating of annoyance as well as the SNQs based on sound pressure levels generated by the standard tapping machine. It was also detected that impact rubber ball gave better correlations between the SNQs and the subjective rating of floors, but not necessarily better than the SNQs based on the standard tapping machine [15]. The authors stated that the highest correlations with subjective rating were achieved with $L_{n,w} + C_I$ [16]. None of the 19 floors had floor covering like carpet, laminate flooring or vinyl. This means that the relation of the results to real impact sounds in dwellings is not clear.

In the psychoacoustic experiment conducted by Späh et al [18], four wooden floors and one concrete floor were rated by the SNQs defined in the standard ISO 717-2 [12]. Also alternative SNQs presented by Gösele [19], Fasold [20], Bodlund [14], Hagberg [21] and Ljunggren et al [22] were calculated. Also the rubber impact ball and modified tapping machine [17] were used as a sound source. In addition to the wooden floors, two types of concrete floors were measured: 140 mm thick concrete slab and this slab with floating floor of 50 mm thick cast concrete on 25 mm thick mineral wool. Five floor coverings were used in all tests. A part of the wooden floors was measured in the field, and the rest in the laboratory. For the psychoacoustic experiments, walking of female and male walkers was recorded both in the laboratory and in the field. In the laboratory, the male walkers wore shoes and socks and the female walker hard-heeled shoes. Another impact sound source used in the psychoacoustic experiment was drawing of a chair. Two psychoacoustic experiments were made with 18 and 22 subjects. From the SNQs based on the unmodified standard tapping machine, $L'_{n,w} + C_{I,50\text{-}2500}$ (R^2 = 0,63) and the SNQ suggested by Hagberg [21] resulted in highest correlation with subjective rating (R^2 = 0,58).

1.2 Insufficiency of research evidence

On the basis of the recent psychoacoustic experiments it is possible to conclude that the SNQs which were developed for rating of heavy concrete floors in the 1950s are not necessarily applicable to rating of lightweight floors. The survey in residential buildings by Ljunggren et al. [23] also indicates that low frequency impact sounds are especially related to lightweight floors.

As Späh et al [18] state, an adequate SNQ for rating of impact sound insulation should comprise all floor constructions, lightweight as well as massive floors. At the moment, a great majority of European dwellings are constructed of concrete or other massive structures [24]. There is earlier research referring to importance of low-frequency sound in the case of certain heavy-weight floors [25, 26, 27, 28]. A recent study dealing with concrete floors [29] showed that walking with socks generates sound pressure levels which at frequency bands below 100 Hz are higher than the sound pressure levels generated by walking with hard-heeled or soft-heeled shoes. The results also confirmed that compared with walking on other floor coverings on load-bearing concrete slab, walking on floating floors may generate 5–15 dB higher sound pressure levels below 100 Hz. From the walking sounds and sounds generated by other impact sound sources, different noise ratings were calculated. The noise ratings of walking with hard-heeled shoes correlated strongly with the SNQs based on the tapping machine. The correlation coefficients between the noise ratings of chair moving, superball bouncing and SNQs based on tapping machine were also strong. Walking with soft-heeled shoes correlated strongly with the SNQs only in the case of one walker out of three. No statistically significant correlation between the noise ratings of walking with socks and the SNQs was detected.

The above referred study [29] was based on calculated loudness of measured spectra of walking sounds and other impact sound sources. Hongisto et al [30] have shown that in the case of airborne sound insulation the results dealing with subjective loudness differ from those regarding to annoyance. Annoyance, as it is defined in ISO 15666 [31], is considered as a predecessor of more serious health effects. Therefore, annoyance might be a better measure for sound insulation in apartment dwellings than loudness.

The results of the earlier study [29], which was based on objective rating of loudness, can be verified only with psychoacoustic experiments. This kind of study cannot be conducted in the field as the sound sources cannot be controlled in field conditions. In the few works studying this field, the connection to real floors in buildings is not always clear as the floors did not have any floor covering in many studies [10, 11, 15, 16]. The amount of impact sound types has also been limited: Nilsson & Hammer [10, 11] used only two sound sources. The variation of structural types of the floors has been limited, too, as the focus has been in wooden floors in many studies [15, 16, 18]. Therefore, there is a need for a psychoacoustic experiment concerning impact sound insulation of concrete floors.

A reliable correlation analysis on the basis of psychoacoustic test requires quite a large amount of data. In many of the psychoacoustic experiments referred in the chapter 1.1., the number of the subjects has been rather small, around 20 persons or less [10, 11, 15, 16, 18]. The risk of coincidence and resulting wrong conclusions increases with decreasing number of subjects. Considering airborne sound insulation, there is a recent study presenting results of psychoacoustic experiments conducted with an extensive amount of subjects [30]. Regarding impact sound insulation, it can be said that the scientific basis of the SNQs for impact sound insulation is insufficient. Thus, there is a need for a psychoacoustic experiment with a number of subjects similar to reference [30].

1.3 Purpose of the study

The purpose of our study was to determine the associations between subjective ratings of impact sounds and various standardized and alternative single-number quantities of impact sound insulation. The focus was on concrete floors with various kinds of floor coverings. The present standardized single-number quantities expect that the main impact source is walking with hard-heeled shoes. This sound type does not necessarily reflect the most typical impact sounds in all countries [6, 29].

Special care was taken that large number of subjects was used to guarantee strong statistical power, large range of impact sound insulation levels were involved, and that various kinds of realistic impact sounds were used in order to reflect the real situation in residential dwellings. It has been suggested that the measurements should be extended to 20 Hz [23]. However, no evidence about measurement uncertainty below 50 Hz does exist. Because of this, our study focused on frequency range 50–5000 Hz. Light-weight constructions were not included to our study.

2 MATERIALS AND METHODS

2.1 Overall study design

This is an experimental laboratory study where the subjects judged 44 recorded impact *sounds* in a psychoacoustic laboratory. The impact *sounds* were recorded in an impact sound insulation laboratory where nine floor constructions were installed one after the other (later: **floor types F1-F9**). Five different types of impact sounds (later: ***sound types S1-S5***) were recorded for each floor type. However, one impact sound was excluded for one construction (F6S5) because the sound of chair moving could not be produced properly with the very soft floor covering in question.

Several standardized and non-standardized SNQs were determined for each floor type based on their impact sound pressure level measured using tapping machine [32]. Thereby, the data could be used to determine how well the SNQs predict the subjective judgments of each sound type.

The independent variables are the *SNQ*s determined for the nine floor types and the five *sound types*. The dependent variables are two subjective measures: *loudness* and *annoyance*.

2.2 Subjects

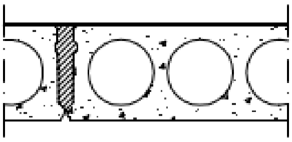
Fifty-five voluntary subjects (25 male, 30 female) participated in the experiment. The age varied from 20 to 57 years (mean 27, median 25, standard deviation 9). Subjects were invited via university student organizations. The subjects were told that the purpose of the experiment was to evaluate different sounds. The subjects signed a letter where they were informed that they are free to withdraw from the experiment and leave the psychoacoustic laboratory for any reason and that all materials gathered are treated confidentially by the research institute.

The presumptions were normal hearing ability, Finnish native language and currently residing in a multi-storey building. The latter condition was judged important because the experiment deals with sounds usually heard in multi-storey buildings and we wanted to avoid subjects who had no recent experience of living in such an environment. None of the subjects were occupied by authors' research institutes nor had participated in any prior experiment in the laboratory. The subjects were given a 20 euro gift token for their participation after the completed experiment. The subjects were informed beforehand about the loudspeakers in the psychoacoustic laboratory. None of the subjects withdrew from the experiment.

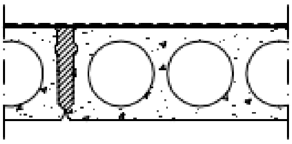
2.3 Floor types and measurements

Our study involves eight various floor coverings **F2-F9** installed on the top of the load-bearing concrete floor construction (**F1**) one after the other during the summer of 2012 (**Figure 1**). The floor coverings were chosen to represent most commercial alternatives ranging from bare concrete floor to floating floor. The constructions were discussed in detail in Ref. [29].

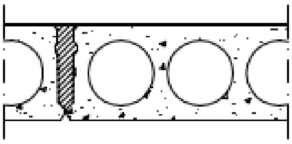
The normalized impact sound levels L'_n [dB] were measured according to ISO 140-7 [32] using the tapping machine (**Figure 2**). The measurements done at Upofloor impact sound laboratory in Nokia have been described by Kylliäinen et al. [29]. The dimensions of the receiving room of the laboratory were: width 4,0 m, length 6,0 m and height 2,5 m. The volume of the receiving room was 60 m^3. During these measurements, the receiving room of the impact sound laboratory was empty from additional sound absorbers – they were only used during natural impact sound recordings to ensure that the room acoustics during the recordings corresponds to the room acoustics of furnished rooms in Finnish apartments.



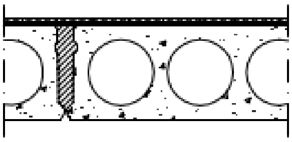
F1
- no floor covering
- levelling compound
- hollow core slab 265 mm (380 kg/m2)



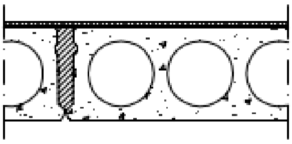
F2
- cushion vinyl (Upofloor Estrad), ΔL_w = 2 dB
- levelling compound
- hollow core slab 265 mm (380 kg/m2)



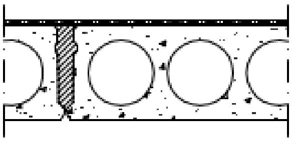
F3
- cushion vinyl (Upofloor Upostep), ΔL_w = 21 dB
- levelling compound
- hollow core slab 265 mm (380 kg/m2)



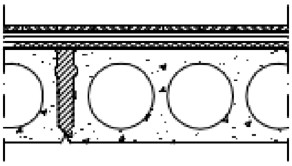
F4
- multilayer parquet 14 mm (Karelia Upofloor)
- underlayment 3 mm (Tuplex), ΔL_w = 20 dB
- levelling compound
- hollow core slab 265 mm (380 kg/m2)



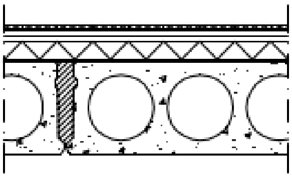
F5
- wall-to-wall carpet (Epoca Compact), ΔL_w = 21 dB
- levelling compound
- hollow core slab 265 mm (380 kg/m2)



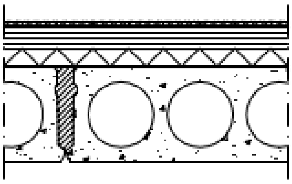
F6
- wall-to-wall carpet (Milliken), ΔL_w = 29 dB
- levelling compound
- hollow core slab 265 mm (380 kg/m2)



F7
- multilayer parquet 14 mm (Karelia Upofloor)
- underlayment 3 mm (Tuplex), ΔL_w = 20 dB
- 2 x plasterboard 15 mm (Gyproc GL 15)
- mineral wool 13 mm (Isover VKL)
- levelling compound
- hollow core slab 265 mm (380 kg/m2)



F8
- multilayer parquet 14 mm (Karelia Upofloor)
- underlayment 3 mm (Tuplex), ΔL_w = 20 dB
- 2 x plasterboard 15 mm (Gyproc GL 15)
- mineral wool 50 mm (Isover FLO)
- levelling compound
- hollow core slab 265 mm (380 kg/m2)



F9
- multilayer parquet 14 mm (Karelia Upofloor)
- underlayment (Tuplex), ΔL_w = 20 dB
- 4 x plasterboard 15 mm (Gyproc GL 15)
- mineral wool 50 mm (Isover FLO)
- levelling compound
- hollow core slab 265 mm (380 kg/m2)

Figure 1. Floor constructions.

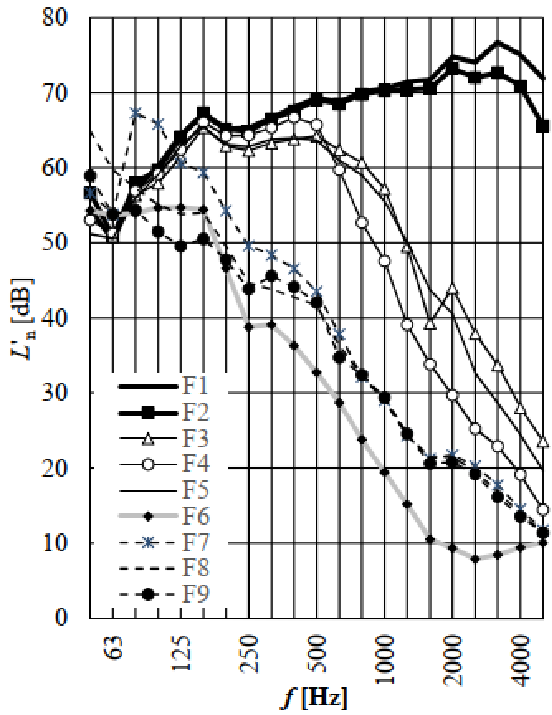


Figure 2. Normalized impact sound pressure levels of the floor constructions.

2.4 Sound source and single-number quantities (SNQ)

Many alternative sound sources for the standard tapping machine have been developed. Among them are the modified tapping machine, rubber impact ball and bang machine. The impact ball has been studied extensively in Japan and Korea. It has been shown that for certain types of concrete floors, the impact ball leads to good correlation between physical measurement and subjective rating [33]. A suitable SNQ to be used in objective rating of concrete floors with impact ball as a sound source has also been studied [34, 35].

It seems probable that the unmodified standard tapping machine will remain as the official impact sound source in Europe [36]. According to Gover et al [15, 16], the modified tapping machine, rubber impact ball or bang machine do not necessarily correlate better with subjective rating of walking sounds than the standard tapping machine. These results were obtained with wooden floors without floor covering, which means that the relation of the results to real impact sounds in dwellings is not clear.

There is also some evidence suggesting that modifying the standard tapping machine or replacing it with some other sound source is not necessary, and the problematics of the correlation between the SNQs and subjective rating of floors should be approached by defining a better SNQ including a better reference curve [37]. Because of these findings, only the standard tapping machine was used as a sound source in our study for the determination of the SNQ's of the nine floors.

Eight SNQ's were determined for each floor type (**Table 1**) and rounded to 0,1 dB [38]. In Finland, the maximum allowed value for $L'_{n,w}$ is 53 dB. All the floors studied here do not fulfil this requirement and in some cases, the SNQ was much lower than the allowed maximum. The purpose of the psychoacoustic experiment was not to study floors that fulfil the requirements but to study how people rate different impact sound spectra. Field measurement results of floors used in Finland can be found in references [39, 40]. In practice, floors giving lower and larger $L'_{n,w}$ than the maximum allowed value in Finland are used in our experiment. The SNQ's were denoted as follows:

- $L'_{n,w}$ according to ISO 717-2 [38]
- $L'_{n,w+}C_I$ according to ISO 717-2 [38]
- $L'_{n,w} + C_{I,50\text{-}2500}$ according to ISO 717-2 [38]
- $L'_{n,w,Fas}$ starting at 100 Hz [20]
- $L'_{n,w,Fas,50}$ starting at 50 Hz [20]
- $L'_{n,w,Ger}$ [41]
- $L'_{n,w,Bod}$ [14]
- $L'_{n,w,Hag}$ [21]

Table 1. The values of the single-number quantities [dB] for nine floor types.

	Floor type								
SNQ	F1	F2	F3	F4	F5	F6	F7	F8	F9
$L'_{n,w}$	79,9	77,7	58,7	59,1	58,5	42,7	50,1	43,2	41,3
$L'_{n,w} + C_I$	66,7	65,8	58	59	58	44,7	53	45	42,1
$L'_{n,w} + C_{I,50\text{-}2500}$	66,7	65,8	58,1	59,1	58,1	47,3	55,9	52,4	47,6
$L'_{n,Fas}$	68,4	67,3	59,4	60,4	59,4	44,7	52,1	45,2	43
$L'_{n,Fas,50}$	68,4	67,3	59,4	60,4	59,4	49	55,6	52,2	47,8
$L'_{n,Ger}$	66,4	65,6	58,4	59,8	58,6	41,9	50,3	43,6	41,5
$L'_{n,Bod}$	66	65,9	62,6	63,9	62,8	56,5	62,8	59,8	55,3
$L'_{n,Hag}$	68,7	67,8	60,7	61,8	60,5	54,5	61,2	61	56,1

2.5 Recordings of natural impact sounds

After the measurements with the tapping machine, additional sound absorbers were installed to the receiving room of the impact sound laboratory to enable the sound recordings of natural impact sounds in such a room acoustic environment which resembles normal living rooms. The absorbents were placed to the floor and walls to achieve a reverberation time shown in **Figure 3**. The data corresponds relatively well with the reverberation time measured in Finnish living rooms and bedrooms [42, 43].

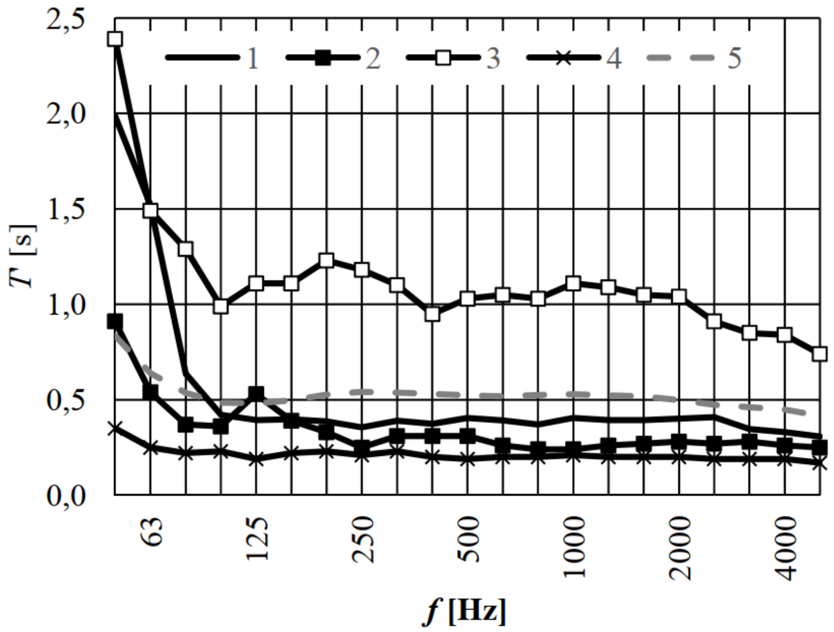


Figure 3. Reverberation time in the receiving room of the impact sound insulation laboratory during the recordings (1) and in the psychoacoustic laboratory (2). Comparison is made with the maximum (3) and minimum (4) of 207 measured furnished living rooms. Dashed grey line (5) shows the mean of furnished living rooms [43].

Five different impact sounds **S1-S5** (independent variable: *sound type*) were recorded on the laboratory for each floor type F1-F9. The *sound types* were:

- S1 - Walking with hard shoes
- S2 - Walking with socks
- S3 - Walking with soft shoes
- S4 - Super all bouncing
- S5 - Chair moving

The walker was in all cases a male person (weight 86 kg, height 188 cm, age 22 years). The recordings of this walker were chosen to the psychoacoustic experiments as the loudest of the three walkers described in [29]. The two other walkers generated lower sound pressure levels but the shapes of the sound spectra generated by them were similar to the chosen walker. The super ball was chosen to represent one possible form of children’s playing. The ball (50 g) is made of synthetic rubber being very elastic so that it bounces nearly back to the dropping height. The walking paths and the walking tempo as well as other sound sources were described in [29].

Two-channel recordings were performed on the impact sound laboratory’s receiving room with Sinus Harmonie and the Samurai 1.5 software (*.wav, sampling rate 44.1 kHz). The separation of the microphones was 22 cm. The microphone and the preamplifier were GRAS 40F and GRAS 26AK respectively. The recording system was calibrated before the recordings (B&K 4231). Simultaneously with the recordings of the five *sound types*, the equivalent sound pressure level spectrum of the sound was measured to enable the identification and adjustment of the recording in the audio filtering stage.

The background noise level of the receiving room of the impact sound laboratory (absorbents installed) is shown in **Figure 4**. The peak levels of the stimuli (except sound type S3, walking with soft shoes) exceeded the background noise level of the psychoacoustic laboratory and the quality of the sounds was good for post-processing. Noises relating to the recording process or background noise during recording of the impact sounds could not be detected.

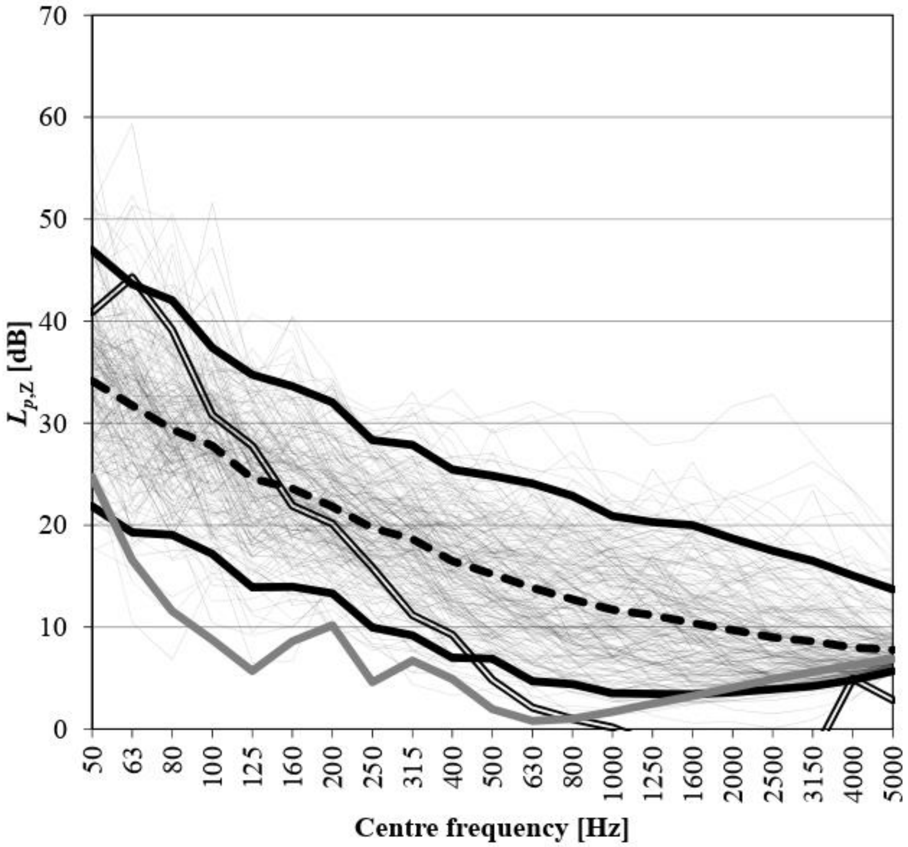


Figure 4. The linear background noise level of the receiving room of the impact sound laboratory during the recordings (grey line, 15,6 dB $L_{A,eq}$), and in the psychoacoustic laboratory (black double line, 22,8 dB $L_{A,eq}$). Black lines show the 95 % and 5 percentiles and dashed black line the mean of background noise levels in Finnish living rooms (23,6 dB $L_{A,eq}$).

2.6 The experimental sounds

Forty-four twenty-seconds-long *experimental sounds* (later: *sounds*) were presented to the subjects. The sounds are abbreviated by ***FXSY***. Letter S refers to sound type which had five values: X = 1 to 5. Letter F refers to floor type, which had nine values: Y = 1 to 9. The A-weighted levels of the experimental sounds are shown in **Table 2**. The spectra of the experimental sounds are shown in **Figure 5**.

Table 2. The A-weighted target levels [dB] of the 45 experimental sounds in the occupants' position. Experimental sound S5F6 does not exist because moving the chair on the surface of the very soft floor covering was not possible.

Sound type	F1	F2	F3	F4	F5	F6	F7	F8	F9
S1	32,0	30,5	29,4	34,9	24,3	17,2	27,0	22,0	19,9
S2	26,9	28,2	28,7	27,0	27,7	16,9	31,6	31,2	25,3
S3	21,0	22,0	20,7	23,9	18,2	15,2	23,2	19,2	18,0
S4	29,7	29,0	31,7	31,1	29,3	29,4	26,8	22,3	17,4
S5	37,7	29,6	20,7	32,3	24,0		29,0	16,4	16,5

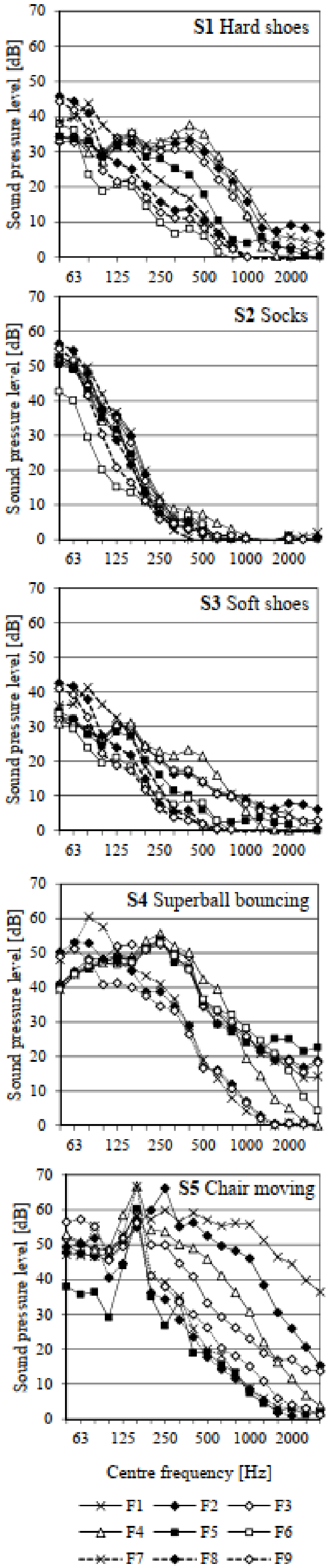


Figure 5. Spectra of sound types for each floor type expressed as spectra of maximum sound pressure levels.

2.7 The psycho-acoustic laboratory

The experiment was conducted in the psychoacoustic laboratory (30 m^2) at the Finnish Institute of Occupational Health (**Figure 6**). The dimensions of the laboratory are: width 4,6 m, length 6,7 m and height 2,7 m. The volume of the psychoacoustic laboratory is 83 m^3. The background noise level (**Figure 4)** was measured using a highly sensitive condenser microphone (B&K 4179 and B&K 2660 preamplifier). The background noise level $L_{A,eq}$ in the psychoacoustic laboratory corresponds with the mean value measured in Finnish living rooms [43], but there are differences in sound spectra. In the psychoacoustic laboratory, the sound pressure levels were higher at the low frequencies but lower at mid and high frequencies. The reverberation time (**Figure 3)** corresponds well with the range measured in Finnish living rooms [42, 43].

Figure 6. A photograph of the laboratory showing the suspended ceilings where the four loudspeakers were installed.

2.8 The playback system

The National Building Code of Finland [44] includes a requirement according to which the weighted normalized impact sound pressure level $L'_{n,w}$ shall not exceed 53 dB between dwellings in multi-storey buildings. The values measured in buildings are usually larger in vertical direction than in horizontal direction. There are also studies suggesting that the vertical direction might be experienced as the most annoying [e.g. 45]. Therefore, it was justified to concentrate on vertical direction.

The subjects sat at the workstation during the experiment. The experimental sounds were reproduced by four active loudspeakers (Genelec 8020B) installed above the suspended ceiling in the periphery of the psychoacoustic laboratory. The levels of individual speakers differed less than 1 dB ($L_{A,eq}$). The speakers were not visible to the subjects (**Figure 6**). In addition, one subwoofer (Genelec 7050B) was located on the floor behind a heavy curtain.

The sounds were played using a standard Windows player (Multimedia control). The playback computer was located behind the curtain 4 meters away to avoid the increment of background noise level. The computer was connected to a sound card (Fireface RME 400), which controlled the four speakers and the subwoofer. The output levels of the four ceiling speakers were adjusted so that the sound pressure level caused by each speaker was similar in the subject's position.

2.9 Audio filtering of *experimental sounds*

The main purpose of the audio processing was that the level in the occupants' position corresponded with the spectrum measured in Nokia impact sound insulation laboratory during the recordings. The effects of the room and the playback system were compensated using audio filtering. The spectrum of each *sound* in the psychoacoustic laboratory was measured with a real time analyser (Nor 840).

The measurement of each *sound* was performed in the occupants' position in six fixed measurement points. The measurement points were selected to reflect the most probable positions of the subject's head and ears. The expected volume of the subject's head was 25x25x20 cm (0,012 m^3). Two measurement points were taken in the heights of 1.1, 1.2 and 1.3 m. The level was measured with a ½'' condenser microphone (NTI M2010, class 1 in the frequency range 20-20000 Hz) and an analyser (B&K Sound Quality software, RME Fireface sound card).

The audio filtering was performed in third-octave bands (Adobe Audition 3.0). First, a 12th order band-pass filter (-3 dB points at 42 and 5800 Hz) was applied to exclude all acoustic stimuli outside the studied frequency range including third-octave bands from 50 to 5000 Hz. Thereafter, third-octave band filters were applied to compensate the effects of the room and the suspended ceiling.

During the preparation of the experimental sounds, up to 30 dB higher playback levels were used to enable reliable spectrum measurements also at those bands where the level fell below the background noise level of the psychoacoustic laboratory when the real listening level was used. The *difference* of the desired (spectrum from the recordings in Nokia impact sound insulation laboratory) and the measured level (spectrum of the *sounds* in the occupant's position) was determined in each third octave band. The difference was within 2 dB in each octave band from 50 Hz to 5 kHz. Typically, the differences were less than 1 dB. The difference in A-weighted level was less than 0,5 dB.

Before the experiment, all 44 *sounds* were measured in the occupants' position using the real playback level by a researcher who was not directly involved in the research. The measured levels corresponded well with the desired levels.

2.10 Subjective measures

A software was programmed (Microsoft Visual Basic 6) in order to associate the playback of the *sounds* with the questionnaires to the subjects. The subject controlled the experimental procedure (listening to sounds, answering the questionnaires, moving to the next sound) using this software.

The dependent variables of the experiment were three subjective measures: *loudness*, *annoyance* and *acceptability*. The subjects were instructed in the following way before starting the experiment: "*Imagine that you are alone at home in a multi-storey building in silence and peace. You are in a relaxed mind set. You are reading a magazine or a book or you are browsing the internet and you start to hear a sound from neighbouring dwelling upstairs.*"

The background noise level of the psychoacoustic laboratory (**Figure 4**) was larger than the equivalent level of several *experimental sounds* (**Table 2**). However, our pilot tests indicated that nearly all *experimental sounds* were audible because the stimuli were impulsive and the *experimental sounds* originated from the ceiling so that the *sounds* were easily audible despite the low equivalent level.

To assure that the responses really represented audible experiences, we expanded the range of each subjective variable from that used by Hongisto et al [30] to reveal also the true audibility of each sound. If the subject judged the sound as inaudible, they were advised to select "0" in each response scale. The number of subjects giving a notation of an inaudible sound was small. Inaudible ratings were mainly given for the *sounds* F6S2 (25 subjects) and F9S3 (13 subjects). For other combinations, inaudible ratings were only occasional.

Before enabling the judgment of the sound samples, the subject was forced to listen once to the sound sample which lasted 20 seconds. During this period, the sentence "*You hear this kind of sound coming from your neighbour*" was shown in the display. Thereafter, three questions appeared on the screen. The sound sample was repeatedly played until the responses were given.

The *loudness* rating was given after a question "*How loud is the sound?*" The judgment was given on a scale from "0" to "10". The extreme alternatives were verbally labelled by "0: The sound is not heard", "1: Very silent" and "10: Extremely loud". The subjects were instructed to choose "0" if they could not hear the sound at all.

The *annoyance* rating was given after a question "*How annoying is the sound?*" The judgment was given on a scale from "0" to "10". The extreme alternatives were verbally labelled by "0: Not at all annoying because the sound is not heard", "1: Not at all annoying" and "10: Extremely annoying". The subjects were instructed to choose "0" if they could not hear the sound at all.

The *acceptability* rating was given after a question "*Would the sound be acceptable if it could be heard in your own home?"* The judgment was given on a four point verbal scale: "0: Completely acceptable because the sound is not heard", "1: Completely acceptable", "2: Acceptable to some extent", and "3: Definitely not acceptable". A four-point scale was used since the purpose of this question was to enquire about subject's ultimate opinion of the sound using a very simple verbal scale. In our paper, we report only the values of *loudness* and *annoyance* because the correlation coefficients of *acceptability* were very close to those of *annoyance* and the conclusions of our research would not be affected by including the *acceptability* data.

2.11 Experimental procedure

The experiment was conducted between November and December of 2013. One to three subjects per day were tested. The experiment took about 75–90 minutes and consisted of five phases (**Figure 7**): questionnaire, hearing sensitivity test, familiarizing phase, rehearsal phase and experimental phase.

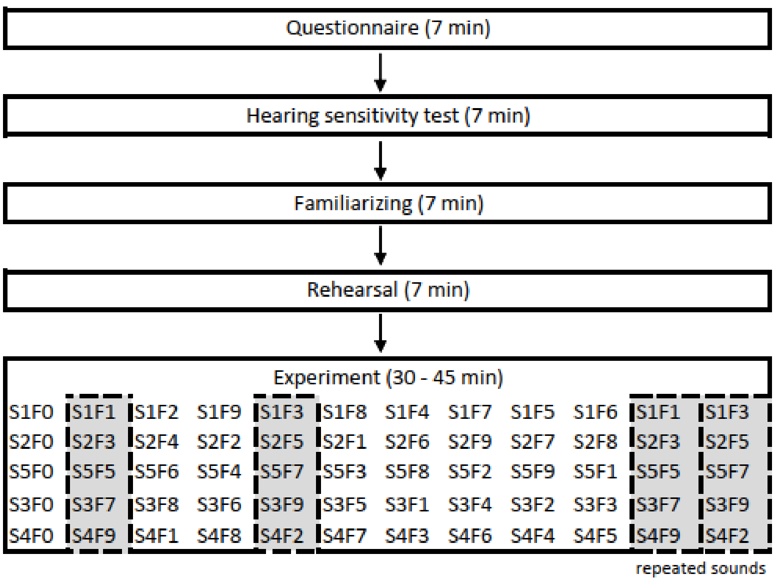


Figure 7. Experimental procedure. This specific presentation order of the *sound types* (rows) and the order of *sounds* (i.e. floors) within each *sound type* concerns only to one subject.

The questionnaire and hearing sensitivity test were done in a silent semi-anechoic room. A hearing sensitivity test was carried out using the Hughson-Westlake method in frequencies 125, 500, 1000, 2000 and 4000 Hz in both ears (Madsen Electronics OB822 Clinical Audiometer). The test was carried out in order to check that the hearing ability was normal in the frequency range of interest. All subjects' hearing was within the normal range for both ears and no hearing loss was detected. Thereafter, the subject moved to the psychoacoustic laboratory.

The familiarizing phase was used to let the subject to become familiar with the forthcoming *sounds* and their levels. This phase consisted of a collection of 15 *experimental sound* samples lasting only 8 seconds. Three samples of each of the five *sound type* were played. The most silent, the average level and the loudest *sound* were played in this order on the basis of the A-weighted levels. The subjects were not yet given the possibility to judge the *sound* in the familiarizing phase.

The rehearsal phase was for practicing the subjective rating. The rehearsal period followed the same procedure as in the experimental phase. Nine *sounds* were used. The results were not analyzed. Before the rehearsal phase, the subjects were instructed both orally and visually about the use of the rating scales. They were encouraged to use the whole scale.

The experimental phase consisted altogether of 60 experimental sound samples; 5 dummy sound samples (F0), 44 experimental sound samples (nine floors per *sound type*), and the repetition of 10 experimental sound samples. The experimental sounds of each *Sound type* were played successively in a cluster, preceded by one dummy sample (F0) and following by the nine *experimental sounds* (F1-F9). Finally, the first and the fourth *experimental sound* of each *sound type* in a cluster were presented again. This was done in order to achieve information concerning the repeatability of the ratings.

The presentation orders of the *sound types* (S1-S5) and of the *floors* (F1-F9) were quasi-randomized between participants (Balanced Latin Square, five and nine alternative order choices respectively). Thus, all kinds of order effects were eliminated.

The dummy samples F0S1, F0S2, F0S3, F0S4 and F0S5 were used to give the subjects some extra time to get used to the new *sound type*. The dummy sound sample for each *sound type* was created by setting the overall listening level L_2 of the sound involving the floor F4 exactly to 30 dB $L_{A,eq}$. Thus, the dummy sound did not correspond to any of the *experimental sounds* but it resembled them to a great extent, as desired. The ratings of the dummy samples were not considered in the analysis.

2.12 Statistical analyses

The primary purpose of our study was to determine the linear correlation coefficients between the subjective measures and the *SNQs* of the floors for each *sound type*. The responses were not normally distributed. Therefore, the correlation analysis was not conducted using the mean of the subjective ratings which has been done usually [15, 16, 30, 46]. Instead, the correlation analysis was now conducted using every individual response instead of the mean of all responses. The resulting *R*-values are smaller compared to those which would have been achieved by using mean ratings. Pearson's correlation coefficients, *R*, were determined, and the coefficients of determination, R^2, were reported. The value of $100 \cdot R^2$ describes how many percent of the change in the subjective judgments can be explained by the change in the value of the *SNQ*. Two examples of the analysis process are shown in **Figure 8**.

The correlation coefficient *R* was considered as statistically significant in the level of p=0,01 (55 data points) when the value exceeds R=0,34. The corresponding limit value for R^2 is 0,12.

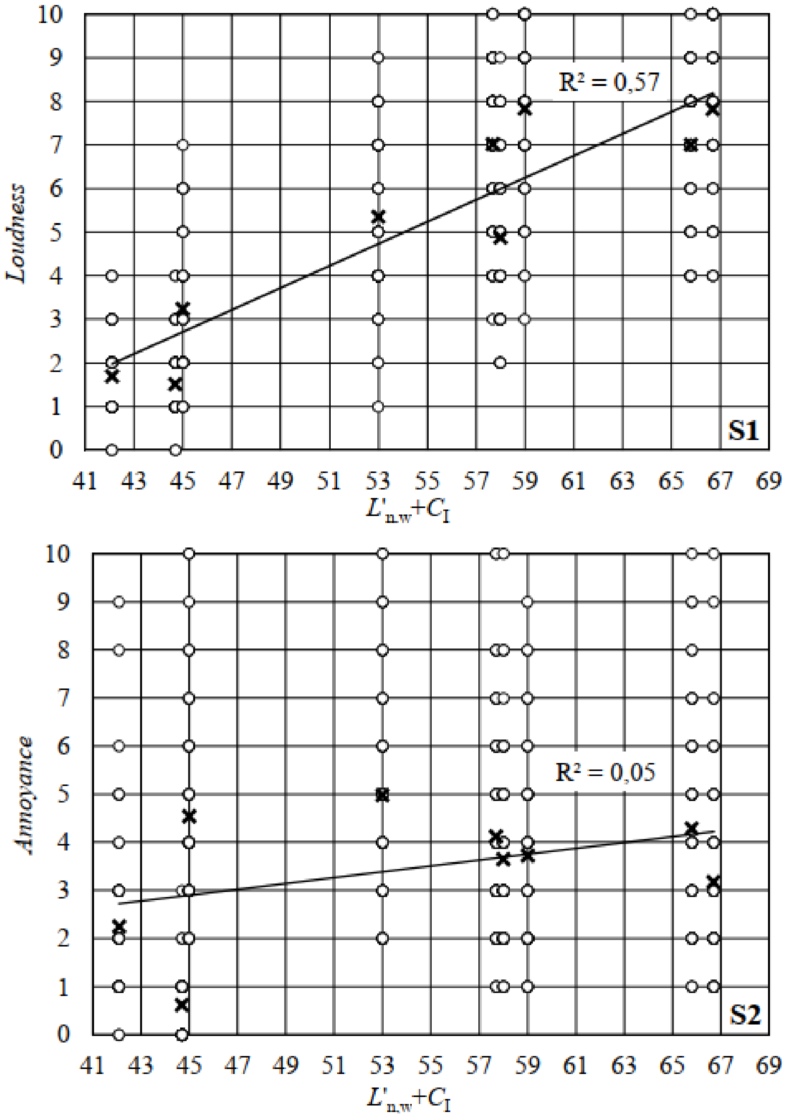


Figure 8. Two examples of the correlation analysis showing a strong correlation (Top) and a weak correlation (Bottom). Circles represent individual responses (overlapping responses are not indicated) and cross represents the mean of all responses.

2.13 Outlier analysis

We performed an outlier analysis in order to confirm that the data used in statistical analysis was free from inconsistent response patterns. Overall glancing of the data indicated that subject #114 used systematically larger values than the other subjects on average. However, the responses seemed to follow a logical pattern. Outlier decisions should be based on solid quantitative evidence. We performed a quantitative outlier analysis by comparing each subjects' response to the mean response of the entire sample. The mean value of the responses may not always be the best single-number descriptor of the data but it was chosen to our outlier analysis. A linear regression fit (y = ax + b) was determined between each subjects' response x and the mean response y. The outcomes of this analysis were the Pearson's correlation coefficient R, the slope a, and the intercept b. Usually, one or two subjects revealed unfavourably low correlation coefficients or very high or low values of either the slope or the intercept. We wanted to test whether a single subject revealed an unfavourable value in all three measures of the outlier analysis. In this case, the reasons were sufficient to remove the subject from the entire analysis.

The results of the outlier analysis are summarized in **Table 3**. Subject #114 appears four times which confirmed our visual findings. Although the correlation coefficients for both *loudness* and *annoyance* were low compared to the mean, the values exceed the level of significance (R=0.34). The subject #114 used a response scale with a very small slope. Contrary to this, subject's intercept values were relatively large (1.67 for *loudness*, 1.73 for *annoyance*). The strategy of the subject #114 was different from the others but the responses were still consistent. In conclusion, all subjects were passed to the final analysis and no outliers were nominated.

Table 3. The outlier analysis showing the mean values of a, b and R of the linear regression for all 55 subjects. The two lowest values (Low1, Low2) of correlation coefficient R, slope a, and intercept b are shown and the corresponding subjects' numbers, S#, are given. Two largest values (High1, High2) of slope and intercept are given and the corresponding subjects' numbers are presented.

	Loudness						*Annoyance*					
	R	S#	a	S#	b	S#	R	S#	a	S#	b	S#
Mean	0,90		0,86		0,74		0,87		0,83		0,96	
Low1	0,64	154	0,42	**114**	-0,60	185	0,49	204	0,38	**114**	-0,76	195
Low2	0,68	**114**	0,59	112	-0,49	142	0,59	**114**	0,46	112	-0,61	142
High1			1,55	181	1,93	104			1,71	122	2,3	204
High2			1,52	124	1,82	131			1,66	134	2,15	191

2.14 Repeatability test

Every subject rated ten *experimental sounds* twice in order to test how accurately the subjects rated the same *sound*. The first and the fourth *sound* of every *sound type* were chosen to the repeatability test.

We performed a t-test (paired samples, 2-tailed, unequal variance) between the two occasions of the same *sound*. Significance level of p=0,05 was used to evaluate the difference between the two occurrences of the same sound.

It should be noted that the number of subjects per *sound* in the repeatability test varied between 0, 11, 22 and 33 because we applied the Balanced Latin Square in eliminating order effects. All *sounds* would have probably been under the repeatability test if we had applied fully randomized order within each *sound type* cluster. Despite of this weakness, we believe that our repeatability test clarifies well how reliable the subjective ratings were.

3 RESULTS

Figure 9 depicts the distribution of subjective loudness of the 44 *experimental sounds*. Distribution of subjective annoyance has been shown in **Figure 10**. The R^2 values between the *single-number quantities* (*SNQ*) and subjective measures (*loudness, annoyance*) are shown in **Tables 4 and 5** for the five *sound types*. The results of the repeatability test are shown in **Table 6**.

Table 4. The R^2-values between the single-number quantities and subjective *loudness* for five sound types. Bolding indicates that the value was statistically significant (p<.01, limit value 0.12). *Sound types* were clarified in **Ch. 2.5**.

SNQ	*Frequency range*	*Sound type* S1	S2	S3	S4	S5
$L'_{n,w}$	100–3150 Hz	**0,47**	0,03	**0,32**	0,11	**0,54**
$L'_{n,w} + C_I$	100–3150 Hz	**0,57**	0,05	**0,39**	**0,16**	**0,50**
$L'_{n,w} + C_{I,50\text{-}2500}$	50–3150 Hz	**0,56**	0,08	**0,37**	0,10	**0,53**
$L'_{n,Fas}$	100–3150 Hz	**0,57**	0,04	**0,38**	**0,16**	**0,50**
$L'_{n,Fas,50}$	50–3150 Hz	**0,55**	0,06	**0,37**	**0,13**	**0,53**
$L'_{n,Ger}$	63–2000 Hz*	**0,58**	0,05	**0,39**	**0,15**	**0,49**
$L'_{n,Bod}$	50–3150 Hz	**0,60**	0,11	**0,41**	**0,13**	**0,44**
$L'_{n,Hag}$	50–3150 Hz	**0,45**	0,10	**0,29**	0,04	**0,51**

* Octave bands

Table 5. The R^2-values between the single-number quantities and subjective *annoyance* for five sound types. Bolding indicates that the value was statistically significant (p<.01, limit value 0.12). *Sound types* were clarified in **Ch. 2.5**.

	Frequency	*Sound type*

SNQ	*range*	S1	S2	S3	S4	S5
$L'_{n,w}$	100–3150 Hz	**0,41**	0,03	**0,26**	0,09	**0,52**
$L'_{n,w} + C_I$	100–3150 Hz	**0,50**	0,05	**0,32**	**0,13**	**0,47**
$L'_{n,w} + C_{I,50\text{-}2500}$	50–3150 Hz	**0,49**	0,08	**0,31**	0,08	**0,51**
$L'_{n,Fas}$	100–3150 Hz	**0,49**	0,04	**0,31**	**0,12**	**0,47**
$L'_{n,Fas,50}$	50–3150 Hz	**0,48**	0,06	**0,31**	0,10	**0,51**
$L'_{n,Ger}$	63–2000 Hz*	**0,51**	0,05	**0,32**	**0,12**	**0,45**
$L'_{n,Bod}$	50–3150 Hz	**0,53**	**0,12**	**0,35**	0,11	**0,43**
$L'_{n,Hag}$	50–3150 Hz	**0,40**	0,09	**0,25**	0,04	**0,51**

* Octave bands

Table 6. Results of the repeatability test. The value describes the mean difference between the second and the first rating of the sound. The number of subjects, N, for each sound is depicted in the following way: Normal font: N=11. Italics: N=22; Underlined: N=33. Empty cell means that this sound was not available in this test. Statistical significance: * p<0.05, ** p<0.01. Loudness is denoted by L and annoyance by A.

Sound type	S1		S2		S3		S4		S5	
	L	A	L	A	L	A	L	A	L	A
F1	*-0.73**	*-0.32*			-0.18	-0.36	*-0.09*	*-0.14*	-0.73	-0.55
F2	*-0.73***	*-0.77***	+0.00	-0.09	+0.82	+0.18	-0.18	-0.27		
F3	+0.55	+0.64	*-0.14*	*-0.27*			+0.36	+0.09	*-0.05*	*-0.09*
F4	*-0.41**	*-0.41**	*-0.05*	*-0.05*	+0.55	+0.82	+0.00	+0.18		
F5			<u>+0.06</u>	<u>+0.03</u>	+0.36	+0.00			*-0.09*	*-0.14*
F6	-0.09	+0.09	+0.18	+0.27	+0.27	+0.09	+0.27	-0.82		
F7			+0.55	+0.27	*+0.23*	*-0.05*	-1.45*	-1.55*	+0.00	-0.55
F8	*-0.95***	*-1.00**			+0.18	+0.09	-0.36	-0.55	*+0.27*	*-0.32**
F9					*+0.18*	*+0.09*	*-0.77*	*-0.27*		

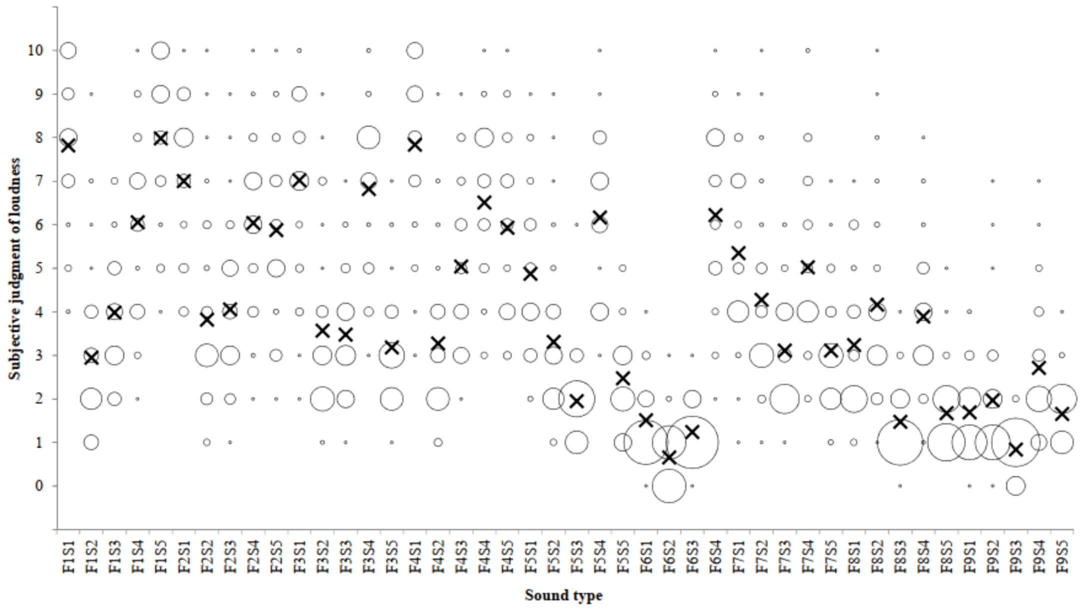


Figure 9. Subjective judgment of loudness of the *experimental sounds* of each floor. The diameter of the circles show the amount of answers (smallest circle: N = 1; largest circle: N = 39). The mean values have been marked with X.

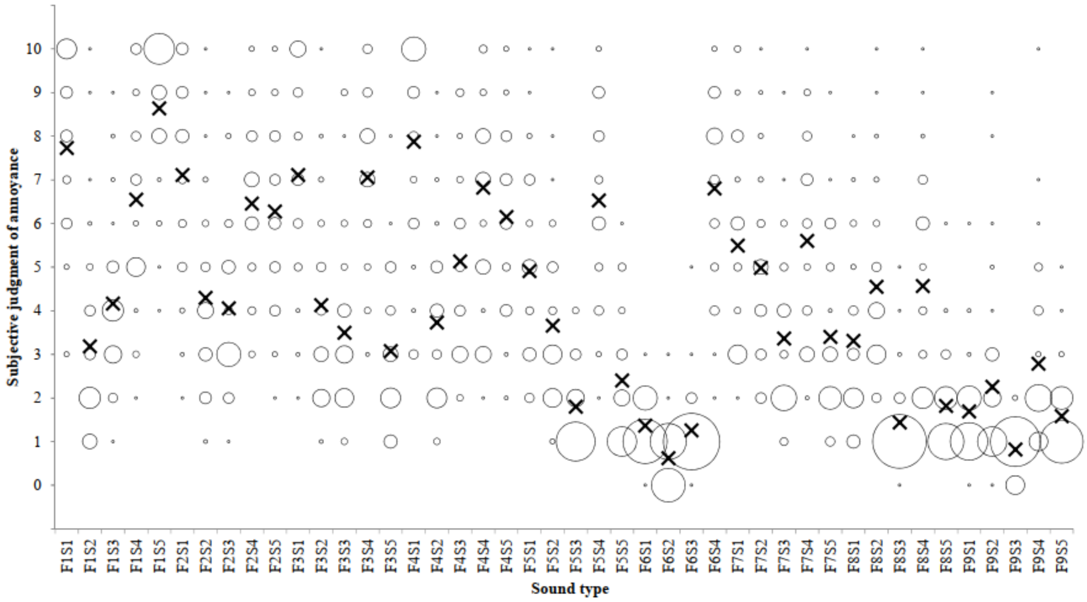


Figure 10. Subjective judgment of annoyance of the *experimental sounds* of each floor. The diameter of the circles show the amount of answers (smallest circle: N = 1; largest circle: N = 40). The mean values have been marked with X.

4 DISCUSSION

4.1 The design of experimental sounds

The levels of *experimental sounds* were relatively low. We took a conscious risk to include also sounds which had a lower equivalent level than the background noise level of the psychoacoustic laboratory (L_{Aeq} = 23 dB). Despite of this, most of the *experimental sounds* were judged audible (**Figure 9**) because the peaks of the sounds were clearly noticeable. The annoyance of the *experimental sounds* got in most cases a slightly higher mean rating than loudness (**Figure 10**). Therefore, we suggest that the design of our experimental sounds and the prevailing masking sound is ecologically valid.

4.2 Main findings

Two groups of *sound types* could be detected. First group consists of *sound types* S1 (hard shoes), S3 (soft shoes) and S5 (chair moving) where statistically significant correlation was found between the *SNQ*s and subjective measures. The other group consists of *sound types* S2 (socks) and S4 (superball bouncing) which were subjectively rated so that very weak correlation between the *SNQ*s and subjective measures was found.

The best indicators of subjective loudness and annoyance regarding *sound types* S1, S3 and S5 were $L'_{n,w} + C_I$, $L'_{n,w} + C_{I,50\text{-}2500}$, $L'_{n,Fas}$, $L'_{n,Fas,50}$, $L'_{n,Ger}$ and $L'_{n,Bod}$. On the basis of average correlations of S1, S3 and S5, the highest R^2 values (0,49) regarding subjective *loudness* were achieved with $L'_{n,w} + C_I$, $L'_{n,w} + C_{I,50\text{-}2500}$ and $L'_{n,Ger}$. Associating with subjective *annoyance*, the best averages (0,44) were achieved with $L'_{n,w} + C_{I,50\text{-}2500}$ and $L'_{n,Bod}$. As $L'_{n,w} + C_{I,50\text{-}2500}$ is among the best associated *SNQ*s with both subjective measures, it could be suggested to be the most suitable *SNQ* if *sound types* S1, S3 and S5 were considered as the most important impact sound sources. This is supported by the results of other studies dealing with lightweight structures [18, 23]. The differences between the *SNQ*s were, however, small and practically as good *SNQ*s might be $L'_{n,w} + C_I$, $L'_{n,Fas}$, $L'_{n,Fas,50}$, $L'_{n,Ger}$ and $L'_{n,Bod}$.

The lowest average R^2 values concerning sound types S1 (hard shoes) and S3 (soft shoes) were associated with $L'_{n,w}$ and $L'_{n,Hag}$. $L'_{n,w}$ does not take the frequencies below 100 Hz into account or weigh large deviations from the reference curve in the way of $L'_{n,w} + C_I$. This indicates that including the frequency range 50–100 Hz into a *SNQ* results in a better correlation between the *SNQ* and subjective rating also in the case of concrete floors. However, $L'_{n,Hag}$ which gives the strongest weight to the low frequencies did not correlate well with the subjective ratings of *sound types* S1 or S3. This might suggest that the low frequencies perhaps should not be weighted too much either.

The low correlation between all *SNQ*s and subjective ratings of *sound type* S2 (walking with socks) can probably be explained on the basis of sound spectra. In the case of *sound types* S1, S3 and S5, the sound spectra were dependent on the floor type (**Figure 5**). Thus, the correlation between the *SNQ*s and subjective rating were statistically significant (**Figure 8**). According to the earlier study [29], the spectra and sound pressure levels of *sound type* S2 are much less dependent on floor covering (**Figure 5**) than for other *sound types*. The difference between the highest and the lowest value of each *SNQ* was, however, large, between 10 and 38 dB depending on the floor type. Therefore, it is consistent that the correlation between the subjective rating of *sound type* S2 and *SNQ*s was smaller than for other *sound types* where the spectral differences of the *experimental sounds* were larger (**Figure 8**).

Another difference between *sound type* S2 (walking with socks) and the other *sound types* was the shape of sound spectrum. Other *sound types* involved sounds at mid-frequencies in addition to low frequencies. Walking with socks generated the highest sound pressure levels below 100 Hz with all floor types. This is quite similar to the spectrum of impact rubber ball used in Japan and Korea which also generates dominant sound pressure levels at frequencies below 100 Hz [33–35]. In the referred Korean and Japanese studies, it has been found that subjective rating of impact ball is highly correlated with A-weighted maximum sound level $L_{\mathrm{AF,max}}$.

The result concerning *sound type* S4 (superball bouncing) differed from the result presented in the previous study [29]. The analysis in Ref. [29] was based on maximum sound spectra and objective loudness of the sounds only, and the both these objective ratings of superball bouncing usually led to strong correlation with the SNQs. Temporal effects were not taken into account in [29] as it is usually expected that the experienced loudness of a time-varying sound is determined by the loudest momentary spectrum when the temporal modulation frequency is less than 10 Hz [47, 48, 49]. Superball bouncing differed from walking as the ball hit the floor around 0,7 times per second, but the frequency of walking was twice as large. Other explaining factor for low correlation between *sound type* S4 and subjective rating is similar to *sound type* S2: according to **Figure 5**, the spectra are quite equal to each other for floor types F1–F6 even though the corresponding values of the *SNQ*s differ by 10 to 27 dB.

4.3 Repeatability test

The repeatability test revealed that either *loudness* and/or *annoyance* ratings differed significantly for 6 sounds out of the 34 sounds under the repeatability test (**Table 6**). The mean values changed from the first rating to the second rating at most by -1.55 in a scale from 0 to 10, that is, 15 % of the whole scale. The mean shift of responses over all 34 sounds was -0.06 for *loudness* and -0.17 for *annoyance* from the first rating to the second rating. That is, the values decreased but very little in most cases.

Significant differences were obtained for *sounds* S1F1, S1F2, S1F4, S1F8, S4F7 and S5F8. We cannot find an explanation why the *sound type* S1 appears frequently in the list (walking with hard shoes). Because significant differences were found both for loud (F1) and silent floors (F8), the level of the sound may not explain the findings. The A-weighted levels of the *experimental sounds* for *sound type* S1 ranged from 15 to 37 dB. Regarding the louder half of the sounds, there was a slight tendency to reduce the second rating which was detected in 65 % of the ratings. In the case of the quieter half of the sounds, the tendency was opposite: the second rating of silent sounds was increased in 58 % of the cases. More experimental data would be needed in order to judge whether this phenomenon is significant enough to be taken into account in future psychoacoustic experiments.

It is also noticeable that the subjective ratings were always reduced for the six abovementioned *sounds*. We cannot find any logical reason for this behaviour. It may be that the subjects wanted to moderate their ratings after they had heard all nine sounds of the cluster. However, this is not the way how they behaved in general since the overall ratings were not changed from the first to the second rating.

Overall, the repeatability test shows that the ratings remain reasonably similar between the two presentations of the same sound and we can relatively safely suggest that the results would not be significantly different if the whole experiment would be repeated. Even though it would be tempting to test whether the correlation coefficients of **Tables 4–5** would change if we use the ratings of the repeatability test (the second appearance of the same sound), this was not found justified, since those sounds which are heard for the second time are in different position compared to those which are heard only once.

4.4 General discussion

It is not absolutely clear, which of the three subjective measures of our study is the most important in a residential environment. Several researchers have focused on loudness since various objective representatives have been published to predict subjective loudness [50, 51]. Loudness is conventionally used for evaluating the overall level of clearly audible and loud sounds. However, loud neighbour sounds seldom exist in living environments on a continuous basis, nor in our experiment. Our impression is that annoyance and acceptability judgments give more information about the potential negative effects of neighbour sounds which are relatively silent but contain information which may disturb the task at hand. This is perhaps supported by the proportion of subjective judgments rating *annoyance* with larger value than *loudness*. The proportion was 75 %, even though the difference between the values of ratings was usually small, the maximum being 0,71. This had also an influence on the correlations between the *SNQ*s and subjective ratings. Regarding especially sound types S1, S3 and S5, the correlations between the *SNQ*s and subjective *annoyance* were in most cases somewhat lower than the correlations between the *SNQ*s and subjective *loudness*. It seems that the *SNQ*s explain the subjective *loudness* better than subjective annoyance.

It is difficult to compare the results of our study with earlier research as the number of subjects and sound types, the generation of experimental sounds and floor types are different. Our result differs from that obtained by Späh et al [18] as they found that $L'_{\mathrm{n,Hag}}$ was the best descriptor for walking noise. The next were $L'_{\mathrm{n,w}} + C_{\mathrm{I,50\text{-}2500}}$ and $L'_{\mathrm{n,Bod}}$ which were among the best *SNQ*s also in our study. Gover et al [15, 16] found that $L'_{\mathrm{n,w}}$, $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$ and $L'_{\mathrm{n,w}} + C_{\mathrm{I,50\text{-}2500}}$ are well correlated with subjective annoyance of walking with socks, $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$

being the best. Other *SNQ*s were not included in their study. The R^2 values in their study were high, over 0,80. This might be explained by the fact that Gover et al calculated correlations from mean ratings and not from all individual responses, as we did. Only wooden floors were included in their study which may explain the difference between their and our results where the correlation between the *SNQ*s and subjective *loudness* or *annoyance* from walking with socks was insignificant.

The materials of our study could be utilized in development of new reference curves which would explain the annoyance and loudness of different impact sounds better than the present *SNQ*s. Our experiment has shown that the low frequency impact sounds are significant in the subjective rating of concrete floors. However, on the basis of the psychoacoustic experiments dealing with lightweight floors it seems possible that the subjective rating of lightweight floors might be based on some other phenomenon than rating of concrete floors. It would nevertheless be impractical to have various SNQs for different floor types. Therefore, it is reasonable to extend this study to cover lightweight floors applying the same methods.

4.5 Limitations and strengths

The age distribution of the subjects was centered on mainly young people in their twenties. This is, however, a common problem of psychoacoustic experiments generally [5, 6, 9], and often the age and gender of the subjects has not been reported at all [10, 11, 15, 16, 18]. On the basis of earlier psychoacoustic experiments, it is not known whether age of the subjects affects the subjective rating of impact sound insulation. Our study, however, has a strong statistical power as the number of the subjects exceeds twice or more the usual number [9, 10, 11, 15, 16, 18]. One benefit of our study is the background of the subjects. Instead of researchers they were people living in dwellings in multi-storey buildings. They were familiar with the soundscape of such buildings. Distribution of the gender of the subjects was better represented than age as 45 % of the subjects were male.

This study concerned massive floors only. This could be considered either as a weakness or as a strength. SNQs have not been compared with each other on the basis of psychoacoustic experiments of concrete floors as extensively as in our study. The floors in our study were all measured and they were all realistic regarding the structural types used in modern buildings [52]. All the sound types were also recorded instead of using artificially produced sounds.

The strength of our study is large number of impact sound types. The number was larger than in psychoacoustic experiments usually [5, 6, 9, 10, 11, 15, 16, 18]. The differences in correlation between the SNQs and the subjective rating of different sound types show that a psychoacoustic experiment cannot be based on one or two sound impact sound sources only.

The lowest frequency band included in our study was 50 Hz even though it is known that real impact sounds may include audible sounds below 50 Hz also in the case of concrete floors [28, 45, 53, 54]. It has recently been suggested by Ljunggren et al [23] that impact sound insulation measurements should be extended to 20 Hz especially when the lightweight floors are concerned. However, the SNQs applied in our research do not consider frequencies outside this range. Furthermore, the recorded maximum sound pressure levels $L_{F,max}$ of the *sounds* exceeded the hearing threshold below 50 Hz at some frequency band only in few cases of the 44 recordings [55]. Therefore, it was absolutely justified to filter out all sounds which did not belong to the investigated bandwidth, whatever happens in field conditions.

It has been shown that measurement uncertainty of impact sound pressure levels at 1/3-octave bands does not rise unacceptably high at frequency range 50–80 Hz, even though the uncertainty of SNQs depends much on the sound spectrum and the shape of the reference curve [22, 56]. Ljunggren et al [23] mention the question of measurement uncertainty at 20–40 Hz, but no results dealing with the uncertainty has been presented. Therefore, extending the frequency range below 50 Hz requires more evidence of the measurement uncertainty.

5 CONCLUSIONS

A psychoacoustic experiment regarding impact sound insulation of concrete floors was carried out. An extensive amount of subjects, 55 people, rated 44 sounds which were recordings of five impact sound sources directed to nine floor types. Eight objective single-number quantities (SNQs) were studied on the basis of correlation analysis between them and subjective ratings of loudness or annoyance.

Statistically significant correlation between the SNQs and subjective ratings were detected in the case of three sound types out of five. Of the SNQs presented in ISO 717-2, the best indicators of subjective loudness and annoyance regarding walking with hard-heeled and soft-heeled shoes and chair moving were $L'_{n,w} + C_I$ and $L'_{n,w} + C_{I,50\text{-}2500}$ followed by $L'_{n,Fas}$, $L'_{n,Fas,50}$, $L'_{n,Ger}$ and $L'_{n,Bod}$. The differences between these five SNQs were small. As $L'_{n,w} + C_{I,50\text{-}2500}$ and $L'_{n,w} + C_I$ were among the best associated *SNQ*s with both subjective measures, they could be suggested to be the most suitable *SNQ* instead of $L'_{n,w}$ if walking with hard-heeled and soft-heeled shoes and chair moving were considered as the most important impact sound sources. Our study was limited to concrete floors. The use of $L'_{n,w} + C_{I,50\text{-}2500}$ has been supported by other studies dealing with lightweight structures. Overall, it seems that the application of $L'_{n,w} + C_{I,50\text{-}2500}$ might be feasible when all kinds of constructions are taken into account.

The subjective rating of loudness and annoyance of walking with socks and superball bouncing were either weakly correlated or not correlated with the SNQs. These sound types cannot be considered as uncommon living sounds. In other words, the present SNQs do not cover all sound types sound types occurring in dwellings. Therefore, there is a need for development of SNQs of impact sound insulation which would correlate better with the general sound types.

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PUBLICATION III

Optimized reference spectrum for rating the impact sound insulation of concrete floors

Mikko Kylliäinen, Petra Virjonen & Valtteri Hongisto

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Optimized reference spectrum for rating the impact sound insulation of concrete floors

Mikko Kylliäinen,[1,a)] Petra Virjonen,[2] and Valtteri Hongisto[2]
[1]*Laboratory of Civil Engineering, Tampere University of Technology, P.O. Box 600, 33101 Tampere, Finland*
[2]*Indoor Environment, Turku University of Applied Sciences, Lemminkäisenkatu 14-18 B, 20520 Turku, Finland*

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It has been long recognized that the single-number quantities presented in the standard ISO 717-2 [(2013) International Organization for Standardization] do not correlate especially well with the subjective judgment of living impact sound sources directed to the floors. The aim of this study was to find single-number quantities which are well associated with the subjective annoyance caused by different impact sounds. Experimental data of laboratory measurements of impact sound insulation of floors and a psychoacoustic experiment was used [Kylliäinen *et al.* (2017). Acta Acust. Acust. **103**, 236–251]. The five studied impact sound types were walking with hard shoes, socks, and soft shoes, super ball bouncing, and chair moving. A fundamental requirement was that the single-number quantities can be expressed as the sum of $L'_{\mathrm{n,w}}$ or $L'_{\mathrm{n}T,\mathrm{w}}$ and a spectrum adaptation term. Reference spectra were derived by the means of a mathematical optimization method. Reference spectra for each sound type were defined separately. An optimized reference spectrum based on all five sound types explained the annoyance of these sound types reasonably well ($r^2 = 0.93$) and better than any of the standardized single number quantities (e.g., $r^2 = 0.86$ for $L'_{\mathrm{n,w}} + C_{\mathrm{I,50\text{-}2500}}$).
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I. INTRODUCTION

The objective sound source for impact sound insulation measurements, the tapping machine, was developed in the 1930s (Hofbauer, 1935; Gastell, 1936). A single-number quantity (SNQ) and a reference curve for rating the impact sound insulation of floors was first standardized in the 1950s in the German standard DIN 52211 (DIN, 1953). The same reference curve was adapted to the first version of ISO 717 (ISO, 1968) and it is still in use as defined in ISO 717–2 (ISO, 2013). Before the first standardization, Gösele (1949) defined requirements for the SNQ, which should be based on an objective sound source and physical measurement, but the results determined by the objective method should correspond as well as possible to the occupants' subjective experience of sounds related to walking on a floor. In addition, the measured SNQs of two floors should be similar if these floors were judged subjectively similar. Mariner (1964) added one more requirement: there should be a method for converting the physical measurement results to a quantitative value corresponding to the subjective experience of the impact sounds.

The problems with the standardized SNQ, weighted normalized impact sound pressure level (SPL) $L'_{\mathrm{n,w}}$, or weighted standardized impact SPL $L'_{\mathrm{n}T,\mathrm{w}}$, were detected already in the 1960s (Mariner, 1964; Fasold, 1965; Mariner and Hehmann, 1967; Olynyk and Northwood, 1968; Watters, 1968). Since that, there have been two strategies for solving the problems. First, there have been suggestions and attempts to modify or replace the standard tapping machine as a sound source (Lindblad, 1968; Watters, 1968; Schultz, 1976; Jeon *et al.*, 2006; Lee *et al.*, 2009; Ryu *et al.*, 2011). There is, however, some evidence indicating that the alternative sound sources to the tapping machine do not necessarily lead into a better association between the objective SNQs and subjective rating (Gover *et al.*, 2011).

It seems probable that the tapping machine will remain as the primary impact sound source (Rasmussen and Machimbarrena, 2014). There is also a recent suggestion that modifying or replacing the standard tapping machine is not necessary. Instead, the strategy solving the problematics concerning the association between the SNQs and subjective rating should be defining a new SNQ based on the tapping machine as a sound source (Zeitler *et al.*, 2013). Several alternative SNQs for rating the impact sound insulation of floors have been suggested since the 1960s (Gösele, 1965; Fasold, 1965; Gerretsen, 1976; Bodlund, 1985; Hagberg, 2010).

Kylliäinen *et al.* (2017) conducted a psychoacoustic experiment dealing with the impact sound insulation of concrete floors. They found that the standardized SNQs, $L'_{\mathrm{n,w}}$, $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$ and $L'_{\mathrm{n,w}} + C_{\mathrm{I,50–2500}}$ were not always well associated with subjectively perceived loudness or annoyance of different impact sound sources. This finding was shown to be valid also for four alternative SNQs (Fasold, 1965; Gerretsen, 1976; Bodlund, 1985; Hagberg, 2010). The reference curves for these SNQs are shown in Fig. 1.

The insufficient association between the SNQs and subjective experience seems to be linked with the Mariner's

[a)]Electronic mail: mikko.kylliainen@tut.fi

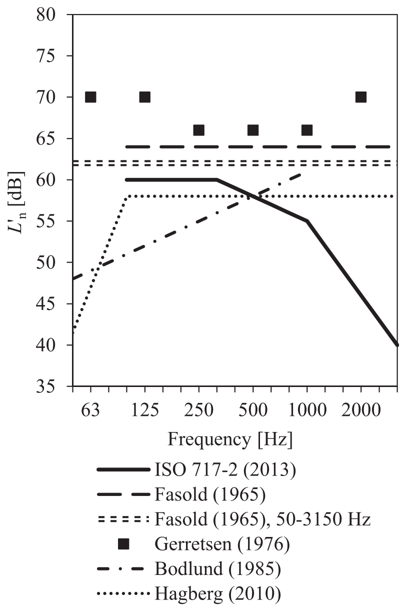

FIG. 1. ISO reference curves and alternative reference curves for the rating of impact sound insulation.

(1964) requirement dealing with the conversion of the physical measurement results to a SNQ corresponding to the people's subjective experience of the impact sounds. Fasold (1965) derived an alternative for the reference curve of DIN 52211 (DIN, 1953) by measuring SPLs of several impact sound sources. Thereafter, he calculated the difference between the measurement results and SPLs generated by the tapping machine. As a result, a mean value for the difference between the SPLs generated by the tapping machine and the actual impact SPLs was found. Adding these differences to subjectively acceptable SPLs at 1/3-octave bands in dwellings resulted in a new reference curve. Gerretsen (1976) measured also differences of the SPLs between the tapping machine and walking. A new reference curve was derived by adding the measured differences to the values of the NR 45 curve, where NR refers to noise rating (ISO, 1971).

The reference curve suggested by Bodlund (1985) is based on the comparison of impact SPLs measured in the field with subjective rating by the people obtained by interviews. The best alternative reference curve was found by generating several guesses. Through a two-phase correlation analysis, the curve producing the best correlation was chosen to the suggested alternative for the ISO reference curve. The same materials added with some newer measurement results and the same method of generating guesses for an alternative reference curve was also used by Hagberg (2010).

The derivation of the four alternative SNQs reviewed above did not apply any mathematical optimization methods. Thus, the best possible reference curves have not necessarily turned up in the earlier studies. This may also explain why the suggested alternative reference curves and SNQs differ a lot from each other (Fig. 1). The psychoacoustic experiment reported by Kylliäinen *et al.* (2017) showed that, for some common impact sounds, no correlation between the subjective loudness or annoyance and any of the objective SNQs was found. They concluded that there is a need for the development of a SNQ, which would correlate better with the general impact sound types. Our study attempts to respond to their conclusion.

Virjonen *et al.* (2016) have already developed optimized reference spectra for airborne sound insulation by applying mathematical optimization to experimental data of Hongisto *et al.* (2014). The mathematical optimization method is an effective and quick method for the derivation of a scientifically justified SNQ. The method also allows for setting constraints that the solution should fulfill. This way, optimization is a more sophisticated method than the guess method applied by Bodlund (1985) and Hagberg (2010) although both methods might result in the same outcome. Kylliäinen *et al.* (2017) studied the subjective responses to five different impact sounds directed to nine floors. The materials of their study provide an opportunity to use the mathematical optimization method for defining new spectrum adaptation terms and reference spectra for the rating of impact sound insulation. Laboratory data are more reliable for deriving alternative reference spectra than data obtained in residential buildings since the sounds and the rating methods are highly controlled.

The purpose of our study is to develop alternative SNQs for impact sound insulation that explain well the annoyance caused by various impact living sounds transmitted from the neighboring dwelling upstairs. Alternative SNQs concern five spectrally different impact sounds (walking with hard shoes, walking with socks, walking with soft shoes, superball bouncing, chair moving) experimentally investigated by Kylliäinen *et al.* (2017). In addition, the purpose is to develop a single SNQ that explains well the annoyance caused by all five impact living sounds.

II. MATERIALS AND METHODS

A. Basic assumptions

The starting point of our study was that the new SNQs can be expressed as the sum of $L'_{\mathrm{n,w}}$ or $L'_{\mathrm{n}T,\mathrm{w}}$ and a new spectrum adaptation term instead of C_{I} or $C_{\mathrm{I},50\text{–}2500}$. In addition, the basis for developing a new reference curve was the use of the tapping machine as the sound source. Furthermore, it was assumed that a new method for rating the impact sound insulation could be found by deriving a better SNQ or reference curve instead of replacing the tapping machine with some other sound source, such as Japanese ball used in ISO 16283–2 (ISO, 2015).

Ljunggren *et al.* (2014) suggested that the measurements of impact SPLs in determining the objective SNQ should be extended to 20 Hz instead of 50 Hz, 100 or 125 Hz used in present standards. However, there is not enough evidence about measurement uncertainty below 50 Hz. In the materials of Kylliäinen *et al.* (2017) which is used also in our study, the maximum SPLs, $L_{F,max}$, of impact sounds did not exceed the hearing threshold below 50 Hz in most cases. Therefore, the frequency range below 50 Hz was ignored. Our alternative SNQs are developed for the frequency range 50–2500 Hz.

B. Experimental data

Experimental data utilized in our study originates from a psychoacoustic laboratory experiment concerning subjective loudness and annoyance of different impact sounds like walking and moving the furniture (Kylliäinen *et al.*, 2017). This section summarizes the methods of that study.

Fifty-five voluntary people (25 male, 30 female) participated in the experiment. Their age varied between 20 and 57 yr. The experiment was conducted in a soundproof psychoacoustic laboratory (Turku, Finland), where the background noise level was 23 dB L_{Aeq} being similar to the typical background noise measured in dwellings (Takala and Kylliäinen, 2013; Kylliäinen *et al.*, 2017). The impact sounds were played from several loudspeakers installed above the suspended ceiling so that the impact sounds were natural. The SPL of the impact sounds in the participant's position varied between 15 and 38 dB L_{Aeq}. Apart from a few exceptions, the participants reported that the impact sounds were audible.

The experiment involved 45 impact sounds. They were created by recording five *sound types* and nine floor types. The impact sounds were recorded in an impact sound insulation laboratory (Nokia, Finland). The background noise level of the receiving room was sufficiently low, 16 dB L_{Aeq}, enabling clear recordings for the psychoacoustic experiment. The floor types consisted of nine floor constructions: a bare 265-mm-thick hollow core concrete slab (F1) and eight different floor coverings (F2–F9) installed on the top of F1. The normalized impact sound levels L'_n [dB] were measured according to ISO 140–7 (1998) using the tapping machine (Fig. 2). The floor coverings and the impact sound insulation measurements have been described in detail by Kylliäinen *et al.* (2015). In short, the floor coverings of constructions F2–F9 were

F2: hard cushion vinyl ($\Delta L_w = 2$ dB),
F3: soft cushion vinyl ($\Delta L_w = 21$ dB),
F4: parquet and soft underlayment ($\Delta L_w = 20$ dB),
F5: hard wall-to-wall textile carpet ($\Delta L_w = 21$ dB),
F6: soft wall-to-wall textile carpet ($\Delta L_w = 37$ dB),
F7: F4 on top of a floating floor 1 (2 plasterboards and 13 mm mineral wool) ($\Delta L_w = 29$ dB),
F8: F4 on top of a floating floor 2 (2 plasterboards and 50 mm mineral wool) ($\Delta L_w = 36$ dB),
F9: F4 on top of a floating floor 3 (4 plasterboards and 50 mm mineral wool) ($\Delta L_w = 38$ dB).

The values in brackets refer to the weighted reduction of impact SPL according to ISO (2013). The normalized impact SPLs L'_n and the values of important standardized SNQs ($L'_{n,w}$, $L'_{n,w} + C_I$, and $L'_{n,w} + C_{I,50\text{–}2500}$) and the impact

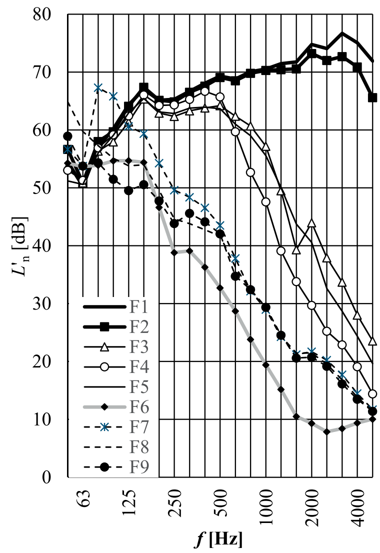

FIG. 2. (Color online) Spectra of normalized impact sound pressure levels of the nine floor types. The floor types are described in Sec. II B.

sound reduction indices R_i calculated according to Scholl (2011) have been presented for each floor type in Table I.

Five different impact *sound types* S1–S5 were recorded in the impact sound insulation laboratory for each floor type F1–F9. The *sound types* were

- S1: walking with hard shoes,
- S2: walking with socks,
- S3: walking with soft shoes,
- S4: super ball bouncing,
- S5: chair moving.

Special attention was paid to keep the forces of these natural impacts constant over the nine floor types.

The participant judged the *loudness*, the *annoyance* and the *acceptability* of each impact sound. The values of *loudness* and *annoyance* were studied further because the *acceptability* correlated very closely to the *annoyance* values. The judgment for *loudness* was given on a scale from 0 to 10, value 0 meaning that the sound was not audible and 10 meaning that the sound is extremely loud. The same scale was used in the judgment of *annoyance*, value 10 indicating that the sound is "extremely annoying" and 0 "not at all annoying because the sound could not be heard." The *annoyance* ratings were usually larger than *loudness* ratings. We used the mean values of subjective *annoyance* (Fig. 3) as a subjective variable in the optimization problem since *annoyance* is closely related to health effects of noise and acoustic comfort.

C. Formulation of the optimization problem

The formulation of the optimization problem is basically the same as used by Virjonen *et al.* (2016). The detailed formulation is explained in the Appendix. The calculation

TABLE I. Measured normalized impact sound pressure levels L_n' and impact sound reduction indices R_i of the nine floor types and the single-number quantities calculated from them.

Floor	F1		F2		F3		F4		F5		F6		F7		F8		F9	
Frequency [Hz]	L_n' dB	R_i dB	L_n' dB	R_i dB	L_n' dB	R_i dB	L_n' dB	R_i dB	L_n' dB	R_i dB	L_n' dB	R_i dB	L_n' dB	R_i dB	L_n' dB	R_i dB	L_n' dB	R_i dB
50	54.5	40.7	56.7	38.5	53.7	41.5	53.0	42.1	51.2	44.0	54.3	40.9	56.7	38.5	64.9	30.3	58.9	36.3
63	50.3	45.9	50.9	45.3	50.9	45.3	51.3	44.9	50.6	45.6	53.6	42.6	53.8	42.4	59.7	36.5	53.8	42.4
80	57.0	40.2	58.0	39.2	56.3	40.9	56.9	40.3	56.0	41.2	53.9	43.3	67.3	29.9	57.3	39.9	54.4	42.9
100	60.2	38.0	59.7	38.5	57.9	40.3	59.2	39.0	59.1	39.1	54.7	43.5	65.8	32.4	55.1	43.1	51.5	46.7
125	64.4	34.8	64.1	35.1	61.4	37.8	62.4	36.7	63.0	36.2	54.7	44.5	60.6	38.5	53.8	45.4	49.5	49.6
160	67.0	33.2	67.4	32.9	65.4	34.9	66.0	34.2	65.4	34.8	54.4	45.8	59.4	40.9	54.0	46.3	50.6	49.7
200	65.1	36.1	65.1	36.1	62.9	38.3	64.2	37.0	63.1	38.1	46.6	54.6	54.3	46.9	49.6	51.7	47.8	53.5
250	65.3	36.9	64.9	37.3	62.3	39.8	64.3	37.9	62.8	39.3	38.8	63.4	49.6	52.6	44.6	57.5	43.8	58.3
315	66.7	36.5	66.5	36.7	63.3	39.9	65.3	37.9	63.8	39.4	39.1	64.1	48.4	54.8	43.8	59.4	45.6	57.6
400	68.1	36.1	67.6	36.6	63.8	40.4	66.7	37.5	64.0	40.3	36.3	67.9	46.6	57.7	42.8	61.5	44.1	60.1
500	69.3	35.9	69.1	36.1	64.2	41.0	65.7	39.5	63.7	41.5	32.7	72.5	43.5	61.7	41.7	63.5	42.0	63.1
630	68.8	37.4	68.5	37.7	62.4	43.8	59.7	46.5	61.0	45.2	28.7	77.5	37.8	68.4	36.3	69.9	34.8	71.4
800	70.1	37.2	69.8	37.4	60.7	46.5	52.7	54.5	59.0	48.2	23.8	83.4	32.2	75.1	32.3	75.0	32.4	74.8
1000	70.5	37.7	70.3	37.9	57.2	51.0	47.6	60.6	55.6	52.6	19.4	88.8	29.0	79.2	29.1	79.1	29.4	78.8
1250	71.4	37.7	70.4	38.7	49.5	59.7	39.1	70.1	50.0	59.1	15.2	94.0	24.3	84.9	24.4	84.8	24.5	84.6
1600	71.8	38.5	70.6	39.7	39.3	70.9	33.8	76.4	43.7	66.5	10.5	99.7	21.2	89.0	21.5	88.8	20.6	89.6
2000	74.8	36.4	73.2	38.0	44.0	67.2	29.7	81.5	40.6	70.6	9.3	101.9	21.7	89.5	21.5	89.8	20.7	90.5
2500	74.1	38.1	72.0	40.2	37.9	74.3	25.2	87.0	32.6	79.6	7.9	104.3	20.2	91.9	19.6	92.6	19.2	93.0
3150	76.7		72.7		33.7		22.9		28.7		8.4		17.7		16.8		16.1	
$L_{n,w}'$ [dB]	79.9		77.7		58.7		59.1		58.5		42.7		50.1		43.2		41.3	
$L_{n,w}' + C_I$ [dB]	66.7		65.8		58.0		59.0		58.0		44.7		53.0		45.0		42.1	
$L_{n,w}' + C_{I,50\text{-}2500}$ [dB]	66.7		65.8		58.1		59.1		58.1		47.3		55.9		52.4		47.6	

method for the SNQ, impact sound reduction index R_{impact} by Scholl (2011), was utilized instead of the formulation of ISO 717–2 ($L'_{n,w}$ plus a spectrum adaptation term) since it is more appropriate for the optimization purposes due to its explicit formulation. R_{impact} [dB] is calculated from impact sound reduction indices R_i [dB] (see Table I) and reference spectrum levels L_i [dB]:

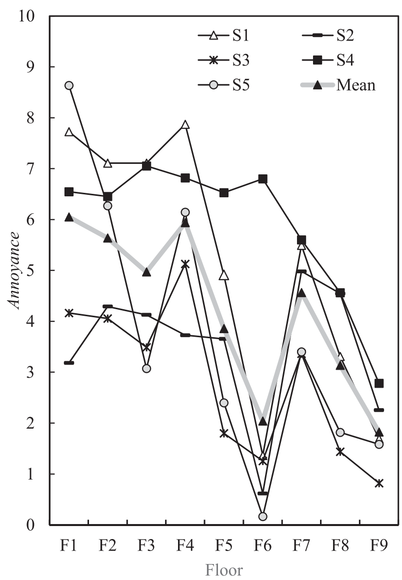

FIG. 3. Mean values of subjective *annoyance* for each combination of impact *sound types* S1–S5 and floor types F1–F9. In addition, the mean over all five *sound types* (Mean) is shown. The number of subjects was 55.

$$R_{\text{impact}} = 10\lg \frac{\sum_i 10^{L_i/10}}{\sum_i 10^{(L_i - R_i)/10}}. \qquad (1)$$

The connection between R_{impact} and $L'_{n,w} + C_{I,50\text{–}2500}$ has been given for standardized tapping machine in Eq. (25) of Scholl (2011). The goal was to find an optimal reference spectrum for each impact *sound type* S1–S5. The optimized reference spectrum for impact *sound type* S1 was called L_{S1}. Notation $R_{\text{imp\_S1}}$ was used for the SNQ which was optimized for impact *sound type* S1, etc.

The subjective variable for each floor type and *sound type* was defined as the mean of the ratings of *annoyance* given by the 55 participants. It was assumed that the subjective variable depends linearly on the SNQ. For each impact *sound type*, such a reference spectrum was sought, that the subjective annoyance had the best achievable least-squares fit with the resulting SNQs. The optimal reference spectrum was determined by formulating the problem as a non-linear optimization problem with constraints, and solving it numerically.

For the formulation of the optimization problem, x_i is the SNQ of the floor type i ($i = 1,\dots,9$), and y_i is the subjective variable for the floor type i. Then, for the floor type i, the SNQ can be calculated from (Scholl, 2011):

$$x_i = 10\lg \frac{\sum_{j=1}^{K} 10^{L_j/10}}{\sum_{j=1}^{K} 10^{(L_j - R_{ij})/10}}. \tag{2}$$

L_j is the level of the reference spectrum at frequency band j.

That is, L_j values are optimized. R_{ij} is the impact sound reduction index for the floor i at frequency band j. The optimization was made using third-octave bands from 50 to 2500 Hz, and thus, $K = 18$.

The impact source power level of the tapping machine is the reference spectrum for R_{impact}. For frequency band j, it is defined as (Scholl, 2011)

$$L_{\text{impact},j} = 82.1 + 10\lg\left(\frac{f_j}{1\,\text{Hz}}\right), \tag{3}$$

where f_j is the 1/3-octave centre frequency of the frequency band j.

$L_{\text{impact},j}$ was used as the initial guess for the algorithm, from which the algorithm started to proceed. The optimized reference spectra were normalized to the tapping machine's total impact power for the frequency range 50–2500 Hz:

$$10\lg \sum_{j=1}^{K} 10^{L_j/10} = 122.9\,\text{dB}. \tag{4}$$

The maximum level difference between adjacent frequency bands of the reference spectrum was limited to 5 dB to avoid too uneven reference spectra.

The optimized SNQ can be expressed as a sum of the weighted normalized impact SPLs $L'_{\text{n,w}}$ and a spectrum adaptation term. For example, spectrum adaptation term for impact sound S1, $C_{\text{I,S1}}$, can be expressed as (see Appendix for the details):

$$C_{\text{I,S1}} = 10\lg \sum_{j=1}^{K} 10^{0,1(L_{S1,j} - 78.2 - 10\lg f_j + L_{n,j})} - 18.9 - L'_{\text{n,w}}, \tag{5}$$

where $L_{n,j}$ is the normalized impact SPL for frequency band j.

D. Solving the optimization problem

The optimization problem was solved using an algorithm for finding the minimum of a constrained nonlinear multivariable function (Matlab, MathWorks, Natick, MA). The algorithm works on the feasible area, i.e., the solution in each iteration fulfills the constraints. For each impact *sound type*, the algorithm stopped since the step size became smaller than the predefined tolerance. The solutions fulfilled the constraints. This means that a local minimum is possible. The calculation was conducted also with another initial guess, which led basically to the same results with all impact sound types.

E. Optimized reference spectrum

In addition to *sound type* optimized reference spectra derived above, we derived also an optimized reference spectrum over all five *sound types*. This is meaningful since the construction performances are declared using a single SNQ which is expected to represent all impact sound types sufficiently well. According to Kylliäinen *et al.* (2017), present standardized SNQs did not predict the *annoyance* of walking with socks or superball bouncing. Therefore, the development of a SNQ that works for several impact sound types, is scientifically justified.

The optimized reference spectrum was called L_{opt} and the SNQ calculated from it $L'_{\text{n,w}} + C_{\text{I,opt}}$. This reference spectrum was derived by adding all 45 experimental sounds (nine floor types times five *sound types*) into the same pool. This was meaningful since all experimental impact sounds were produced in the impact sound laboratory using normal forces (normal walking, normal superball bouncing, normal chair moving) and the listening levels during the psychoacoustic experiment conformed exactly to the recorded levels.

F. Estimating the uncertainty of the reference spectrum

The subjective ratings are dependent on the selection of the participants. If different participants would attend the experiment, the mean of the disturbance ratings might slightly change. To estimate the sensitivity of the reference spectrum, the reference spectrum was calculated 500 times with slightly changed subjective values. The disturbed subjective values were randomly chosen within the 95% confidence interval $y_i \pm l_i$, where $l_i = 1.96 SEM_i$. SEM_i is the standard error of the mean ($N = 55$) of the subjective variable for the floor i. The values of SEM for each floor and each *sound type* are presented in Table II.

III. RESULTS

The mean *annoyance* for impact *sound types* S1–S5 is presented in Figs. 4(a)–4(e) as a function of the standardized SNQ $L'_{\text{n,w}} + C_{\text{I,50–2500}}$. The figures repeat the results of Kylliäinen *et al.* (2017). Poor correlation between *annoyance* and $L'_{\text{n,w}} + C_{\text{I,50–2500}}$ for *sound types* S2 and S4 is obvious.

The mean *annoyance* for impact *sound types* S1–S5 is presented in Figs. 4(f)–4(j) as a function of the *sound type* optimized SNQ. The mean *annoyance* over all five impact *sound types* and all nine floor types as a function of optimized reference spectrum, $L'_{\text{n,w}} + C_{\text{opt}}$, is shown in Fig. 5.

TABLE II. The values of *SEM* for each floor and each *sound type* used in the uncertainty estimation.

	S1	S2	S3	S4	S5
F1	0.28	0.28	0.24	0.31	0.22
F2	0.30	0.29	0.25	0.27	0.28
F3	0.32	0.30	0.25	0.27	0.23
F4	0.29	0.27	0.30	0.27	0.29
F5	0.29	0.26	0.14	0.29	0.21
F6	0.08	0.09	0.10	0.28	0.06
F7	0.30	0.30	0.25	0.30	0.26
F8	0.27	0.28	0.13	0.30	0.14
F9	0.16	0.24	0.07	0.25	0.12

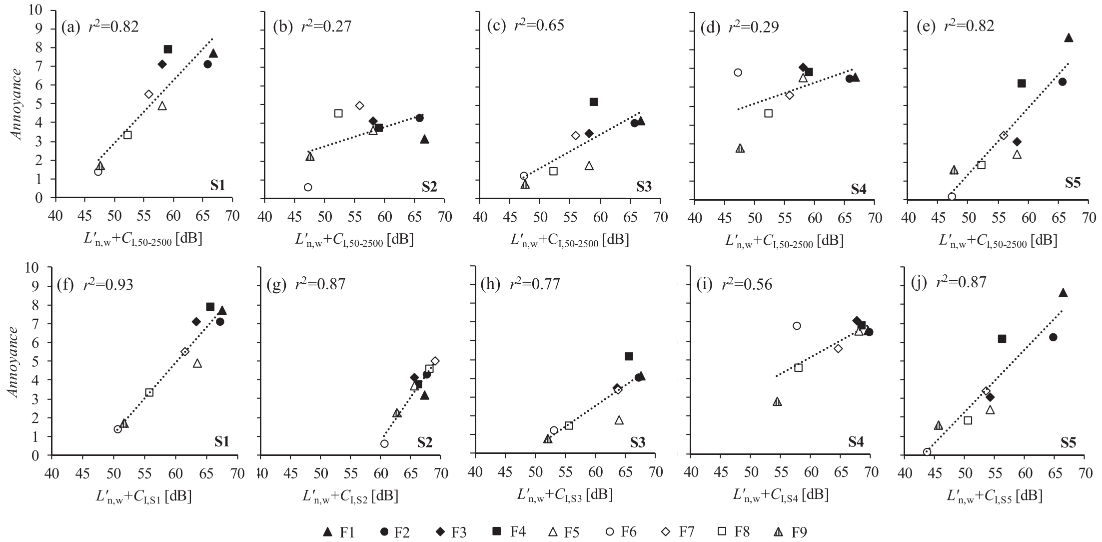

FIG. 4. The relationship between the SNQs and mean *annoyance* for sound types S1–S5 (vertical panels). The symbols depict floors F1–F9. Panels (a)–(e) concern $L'_{n,w} + C_{I,50\text{-}2500}$ and panels (f)–(j) concern the sound type optimized SNQs developed in our study, i.e., $L'_{n,w} + C_{I,S1} - L'_{n,w} + C_{I,S5}$ [panels (f)–(j)]. The squared Pearson's correlation coefficient, r^2, indicates the goodness of the linear fit over the observations.

The optimized reference spectra and the uncertainty limits are presented in Fig. 6. The optimized reference spectra are shown in Table III. The squared correlation coefficients between the standardized and optimized SNQs and the mean *annoyance* are given in Table IV.

The calculation of $L'_{n,w} + C_{opt}$ is based on Eq. (A10). An example of the calculation is shown in supplementary material.[1] It shows also the values of $L'_{n,w} + C_{opt}$ for all nine floors.

IV. DISCUSSION

A. Results

The standardized SNQs $L'_{n,w}$, $L'_{n,w} + C_I$ and $L'_{n,w} + C_{I,50\text{–}2500}$ correlated relatively well with *annoyance* for *sound types* S1 (walking with hard shoes), S3 (walking with soft shoes), and S5 (chair moving). The correlation was poor for *sound types* S2 (walking with socks) and S4 (super ball bouncing).

An optimized reference spectrum yielding a high correlation with *annoyance* could be derived for each *sound type* S1–S5. Compared with the SNQs presented in the standard ISO 717–2 (ISO, 2013), each optimized reference spectrum produced a higher squared correlation coefficient between the optimized SNQ and *annoyance*. Virjonen *et al.* (2016) developed optimized SNQs for airborne sound insulation using the same mathematical method and the resulting SNQs also explained annoyance much better than any of the standardized SNQs. This shows that the mathematical optimization is a consistent and justified method in striving for SNQs associating the physical measurement results to the subjective experience of the impact or other sounds.

Walking with socks (*sound type* S2) is among the most important impact sounds (Gover *et al.*, 2011; Ljunggren *et al.*, 2014; Kylliäinen *et al.*, 2015). Thus, the standardized SNQ should be well associated with the *annoyance* of this *sound type*. The experimental data of Kylliäinen *et al.* (2017) used in our study shows that none of the studied

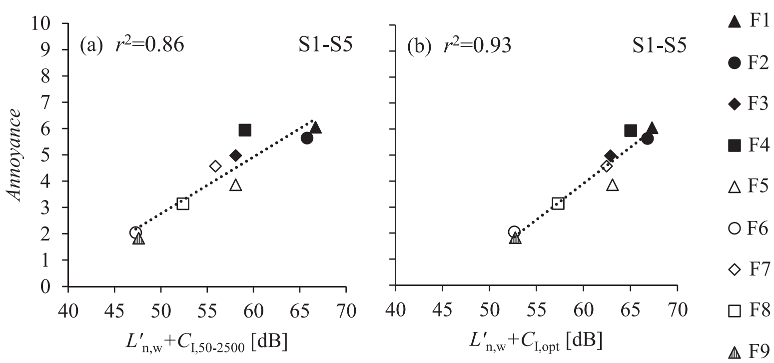

FIG. 5. Mean *annoyance* over all five impact *sound types* and all nine floor types as a function of (a) $L'_{n,w} + C_{I,50\text{-}2500}$ and (b) optimized reference spectrum $L'_{n,w} + C_{I,opt}$. It should be noted that each observation represents the mean of five *sound types* while Fig. 3 showed the means for each *sound type*, separately.

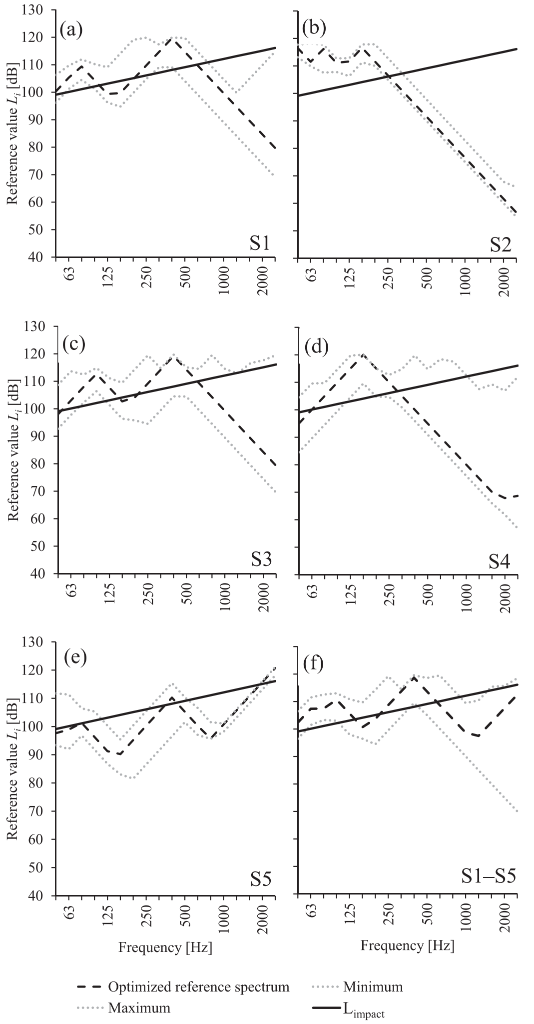

FIG. 6. The sound type optimized reference spectra L_{S1}…L_{S5} (dashed lines) for the impact *sound types* S1–S5 [panels (a)–(e)] and the optimized reference spectrum for all *sound types* S1–S5 [L_{opt}, panel (f)]. The uncertainty limits (minimum, maximum) and the initial guess L_{impact} for the optimization are also shown. L_{impact} is the initial guess used in the algorithm (Sec. II C).

standardized SNQs correlated well with the experienced *annoyance* of walking with socks.

It is very important that we could solve a reference spectrum with a high correlation with *annoyance* also for *sound type* S2 (walking with socks) using the optimization method because this sound type is among the most prevalent neighbor sounds in residential environments (Hongisto *et al.*, 2013). The squared correlation coefficient was 0.87 being significantly higher than those of the standardized SNQs $L'_{n,w}$, $L'_{n,w}+C_I$ and $L'_{n,w}+C_{I,50–2500}$ (r^2 values within 0.09–0.27). Most importantly, all the *sound type* optimized reference spectra gave better squared correlation coefficients than any of the standardized SNQs.

TABLE III. The optimized reference spectra L_{S1}…L_{S5} for the calculation of spectrum adaptation terms of *sound types* S1–S5. The reference spectrum L_{opt} represents the optimized curve which fits well to all five *sound types*.

f [Hz]	L_{S1} [dB]	L_{S2} [dB]	L_{S3} [dB]	L_{S4} [dB]	L_{S5} [dB]	L_{opt} [dB]
50	100	117	98	95	98	102
63	105	112	103	100	99	107
80	109	116	108	105	101	107
100	104	111	113	110	96	111
125	99	112	108	115	91	106
160	100	117	103	120	90	101
200	105	112	104	115	95	104
250	110	107	109	110	100	109
315	115	102	114	105	105	114
400	120	97	119	100	110	119
500	115	92	114	95	105	114
630	110	87	109	90	100	109
800	105	82	104	85	96	104
1000	100	77	99	80	101	99
1250	95	72	94	75	106	98
1600	90	67	89	70	111	103
2000	85	62	84	68	116	108
2500	80	57	79	69	121	113

The optimized reference spectrum for *sound type* S4 (super ball bouncing) produced a better correlation ($r^2=0.56$) than the standardized single-number quantities $L'_{n,w}$, $L'_{n,w}+C_I$ and $L'_{n,w}+C_{I,50–2500}$. However, the squared correlation of *sound type* S4 is clearly lower than for the other *sound types*. One reason might be the narrow spread of *annoyance* responses. However, this cannot be the only reason since equally narrow spread was observed also for *sound types* S2 and S3. The reason for low correlation seems to be floor type F6 involving a very soft wall-to-wall carpet. It produces a low SNQ value but the *sound type* S4 is judged quite annoying. The soft wall-to-wall carpet leads to the lowest SPLs from walking (S1–S3) and chair moving (S5), but S4 is an exception. This *sound type* S4 with wall-to-wall carpet generates similar impact sound spectrum as this sound type with floors F1–F5 (Kylliäinen *et al.*, 2015) which explains this exception. The uncertainty of the optimized reference spectrum of *sound type* S4 is also large (Fig. 4).

The optimization problem was first solved separately for five *sound type* S1–S5. It was found important to derive a single reference spectrum that would explain the *annoyance* responses reasonably for all five *sound types* simultaneously. Therefore, we presented also an optimized reference spectrum, L_{opt} (see Table III), which was used to predict the *annoyance* of all five *sound types*. According to Table IV, the optimized reference spectrum is relatively good since it produced higher r^2 values than any of the standardized SNQs for sound types S1–S3. The values were also reasonably high for *sound types* S4–S5. Thus, the reference spectrum serves the original purpose of being better than any of the standardized SNQs.

B. Uncertainty of optimized reference spectra

The uncertainty estimation shows that minor changes in the optimized subjective variable (mean *annoyance* of 55

TABLE IV. Squared Pearson's correlation coefficients r^2 of the optimized and standardized SNQs for each impact *sound type* S1…S5. The best acquired value per *sound type* is underlined.

SNQ	S1	S2	S3	S4	S5
$L_{n,w}' + C_{I,S1}$	$\underline{0.93}$	0.38	0.75	0.35	0.73
$L_{n,w}' + C_{I,S2}$	0.41	$\underline{0.87}$	0.30	0.01	0.31
$L_{n,w}' + C_{I,S3}$	0.91	0.35	$\underline{0.77}$	0.42	0.69
$L_{n,w}' + C_{I,S4}$	0.87	0.24	0.71	$\underline{0.56}$	0.59
$L_{n,w}' + C_{I,S5}$	0.75	0.26	0.61	0.20	$\underline{0.87}$
$L_{n,w}' + C_{I,opt}$	0.92	0.40	0.75	0.35	0.74
$L_{n,w}'$	0.68	0.09	0.54	0.30	0.80
$L_{n,w}' + C_{I}$	0.83	0.17	0.68	0.44	0.75
$L_{n,w}' + C_{I,50\text{-}2500}$	0.82	0.27	0.65	0.29	0.82

participants) lead to some changes in the reference spectra (Fig. 4). The largest were found for the reference spectra L_{S3} and L_{S4} especially at large frequencies. On the other hand, the uncertainty is very small for *sound types* S2 and S5. This is very important finding for *sound type* S2 where *annoyance* correlated very little with the standardized SNQs. It is therefore suggested that the number of the participants in the psychoacoustic experiments should be relatively large in order to achieve reliable conclusions. The psychoacoustic experiment behind our study involved 55 participants, which is significantly larger than in the earlier experiments involving 10–20 participants (Nilsson and Hammer, 2001; Gover *et al.*, 2011; Späh *et al.*, 2013). This observation is in accordance with Virjonen *et al.* (2016).

For airborne sound insulation, Virjonen *et al.* (2016) did a similar compromising optimization like prescribed before. First, they derived sound type optimized reference spectra for six airborne living sounds (two music spectra, loud speech, baby cry, acoustic guitar, dog bark). Thereafter, they took the grand average of sound type optimized reference spectra. The approach was scientifically justified since it resulted in a reference spectrum which correlated better with *annoyance* than any of the existing SNQs. Rindel (2017) criticized the approach of Virjonen *et al.* by suggesting that "the loud music with rhythmic bass like many types of popular music" should be prioritized instead of taking the grand average over the six living sounds. Although there was no scientific evidence supporting his suggestion, it may be that political rather than scientific reasons decide which impact sounds the residents should be primarily protected from. Therefore, our optimized reference spectrum L_{opt} should be taken as a suggestion whose validity should be verified in further studies.

Correct weighting of the impact sound types is important when the optimized reference spectrum is made in the future. At the moment, there is no statistical data dealing with the prevalence of different impact sounds in residential buildings. We only know, how much residents complain on average about different neighbor sounds, see, e.g., Hongisto *et al.* (2013). This kind of statistics would be beneficial when the significance and weighting of different impact sounds is carried out. The data would be used in defining constraints in the future work dealing with more advanced optimization. However, one must bear in mind that even if the prevalence of different impact sounds is known, reliable development of the optimized reference spectrum is only possible using psychoacoustic laboratory experiments. Therefore, we believe that our optimized reference spectrum can be considered as an alternative reference spectrum in the chain of DIN 52211 (DIN, 1953) and ISO R717 (ISO, 1968), ISO 717–2 (ISO, 2013), Gösele (1965), Fasold (1965), Gerretsen (1976), Bodlund (1985), and Hagberg (2010).

C. Limitations

Our study was based on a single psychoacoustic experiment. It is possible that different results would be obtained for different sound types or different floor types. Our study did not involve, e.g., wooden constructions so that our results may be less valid for wooden floors than for concrete floors. Therefore, it is strongly recommended that similar independent studies are conducted to confirm or question our findings and clarify the remaining questions dealing with, e.g., wooden floors.

V. CONCLUSIONS

Reference spectra for rating impact sound insulation of floors were derived by the means of a mathematical optimization method. An optimized reference spectrum could be developed for each five sound types. Each of them correlates better with the subjective annoyance of the impact sounds than any of the single-number quantities presented in the standard ISO 717–2 (ISO, 2013). In addition, an optimized reference spectrum could be derived which explained the annoyance of all five sound types reasonably well ($r^2 = 0.93$) and significantly better than any of the standardized single-number quantities (e.g., $r^2 = 0.86$ for $L'_{n,w} + C_{I,50\text{–}2500}$).

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APPENDIX

In this Appendix, the details of the optimization problem are presented. The formulation is basically the same as used by Virjonen *et al.* (2016). The subjective variable was assumed to have a linear dependence on the SNQ of the floor type, and the method of linear least squares was utilized.

In least squares fitting the best-fitting curve for data (x_i, y_i), is achieved by minimizing the sum of the squares of the residuals, S, i.e., the differences between the measured value y_i and the value given by the predicted curve. Now the curve is assumed to be linear, and the predicted value is $A + Bx_i$:

$$S = \sum_{i=1}^{n} (y_i - (A + Bx_i))^2, \quad \text{(A1)}$$

where

$$\begin{cases} A = \dfrac{S_{xx}S_y - S_x S_{xy}}{nS_{xx} - S_x{}^2} \\ B = \dfrac{nS_{xy} - S_x S_y}{nS_{xx} - S_x{}^2} \end{cases} \quad \text{(A2)}$$

and

$$\begin{cases} S_{xx} = \sum_{i=1}^{n} x_i^2 \\ S_y = \sum_{i=1}^{n} y_i \\ S_x = \sum_{i=1}^{n} x_i \\ S_{xy} = \sum_{i=1}^{n} x_i y_i. \end{cases}$$

Now, x_i, $i = 1, 2, \ldots, n$ is the SNQ calculated with the reference spectrum, and y_i is the subjective variable, i.e., the average *annoyance* rated by the participants for the floor type i.

x_i was calculated from

$$x_i = 10\lg \frac{\sum_{j=1}^{K} 10^{L_j/10}}{\sum_{j=1}^{K} 10^{L_j - R_{ij}/10}} = 10\lg \sum_{j=1}^{K} 10^{L_j/10} - 10\lg \sum_{j=1}^{K} 10^{L_j - R_{ij}/10}, \quad \text{(A3)}$$

where L_j is the level of the reference spectrum at frequency band j, and R_{ij} is the measured impact sound insulation for the floor type i at frequency band j.

The scope was to find such values for the levels of the reference spectrum L_j at frequency bands $j = 1, 2, \ldots, K$, that the sum of the squares of the residuals, S, [Eq. (A1)] was minimized.

The reference spectrum values for R_{impact} for frequency band j with centre frequency f_j by Scholl (2011) are defined as

$$L_{\mathrm{impact},j} = 82.1 + 10\log\left(\frac{f_j}{1\,\mathrm{Hz}}\right). \quad \text{(A4)}$$

$L_{\mathrm{impact},j}$ was used as the initial guess for the algorithm, i.e., the value from which it started to proceed. The optimized reference spectra were normalized to the tapping machine total impact power for frequency band range 50–2500 Hz:

$$10\lg \sum_{j=1}^{K} 10^{L_j/10} = 122.9\,\mathrm{dB}, \quad \text{(A5)}$$

which forms an equality constraint.

Limiting the difference between adjacent frequency bands below a certain value, *delta*, led to $2(K-1)$ inequality constraints.

In order to find the levels L_j of the optimal reference spectrum, a non-linear optimization problem with constraints was thus formulated:

$$\begin{aligned} &\text{minimize}\, S(L), \\ &\text{over} L \in \mathrm{R}^{\mathrm{K}}, \\ &\text{subject to} \\ &10\lg \sum_{j=1}^{K} 10^{L_j/10} = 122.9\,\mathrm{dB}, \\ &L_{j+1} - L_j - delta \le 0,\ j = 1,\ \ldots,\ K-1, \\ &L_j - L_{j+1} - delta \le 0,\ j = 1,\ \ldots,\ K-1, \end{aligned} \quad \text{(A6)}$$

where $L = (L_1, \ldots, L_K)^T$. S as a function of L is found by substituting Eqs. (A2) and (A3) into Eq. (A1).

The optimization was made using third-octave bands from 50 to 2500 Hz, and thus, $K = 18$. The total number of the floor types was $n = 9$. The difference between the adjacent frequency bands was restricted to $delta = 5$ dB to avoid very strong fluctuations of the resulting reference spectrum. However, there is no scientific explanation to 5 dB. The value could also be 3 or 10 dB.

The problem defined in Eq. (A6) was solved using Matlab (MathWorks, Natick, MA), and SQP-algorithm

SQP-algorithm, Sequential Quadratic Programming, is a gradient-based, iterative method for nonlinear optimization (e.g., Bazaraa *et al.*, 2013). It converts the problem into a quadratic subproblem with linear constraints. The solution of this problem gives the search direction. In this direction, the step size is determined using a line search procedure. Iterations are continued until the search vector becomes sufficiently close to zero. The algorithm operates on the feasible area, which means that after each iteration, the vector L fulfills the constraints.

The SQP-algorithm assumes that the objective function and the constraints are twice continuously differentiable. The objective function is continuously twice differentiable, while $n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2 \neq 0$. The constraint functions are also continuously twice differentiable, when the condition above is valid. This is the case, if the slope B is not vertical. B being vertical would mean that x_i were all the same. This situation could be prevented with a constraint but it was not necessary since a valid solution was found.

The optimized SNQ can be expressed as a sum of the weighted normalized impact SPL and a spectrum adaptation term. To find an expression for the term, the difference between R_{impact} and the optimized SNQ for impact sound type S1, $R_{\mathrm{imp\_S1}}$, is designated with Δ:

$$R_{\mathrm{impact}} = R_{\mathrm{imp_S 1}} + \Delta. \quad \text{(A7)}$$

R_{impact} can be expressed as (Scholl, 2011)

$$R_{\mathrm{impact}} = 119.0 - (L_{n,w} + C_{I,50-2500} + 15) \quad \text{(A8)}$$

and the impact sound reduction index R_j for frequency band j, measured using the tapping machine as the sound source as (Scholl, 2011)

$$R_j = 78.2 + 10\lg\frac{f_j}{1\ \text{Hz}} - L_{n,j}, \tag{A9}$$

where $L_{n,j}$ is the normalized impact SPL for the frequency band j. Using Eq. (A3) for $R_{\text{imp\_S1}}$ and substituting Eqs. (A5), (A8), and (A9) into Eq. (A7), results in

$$\begin{aligned} &L_{n,w} + C_{I,50-2500} + \Delta \\ &\quad \equiv L_{n,w} + C_{I,S1} \\ &\quad = 10\lg\sum_{j=1}^{K} 10^{(L_{S1,j}-78.2-10\lg f_j+L_{n,j})/10} - 18.9. \end{aligned} \tag{A10}$$

[1]See supplementary material at https://doi.org/10.1121/1.5087553 demonstrating the calculation of $L'_{\text{n,w}} + C_{\text{I,opt}}$.

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IV

The measurement uncertainty of single-number quantities for rating the impact sound insulation of concrete floors

Mikko Kylliäinen

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The measurement uncertainty of single-number quantities for rating the impact sound insulation of concrete floors

Author:
Mikko Kylliäinen

Affiliation:
Tampere University of Technology, Department of Civil Engineering, P. O. Box 600, FI-33101 Tampere, Finland, tel. +358 40 849 0825, mikko.kylliainen@tut.fi

Abstract

The ISO standards defining the single-number quantities for rating of impact sound insulation will be revised in the future. In the revision process, a new quantity, impact sound reduction index R_{impact}, has been suggested by Scholl. The suggested revision means that the measured frequency range will change from 100–3150 Hz to 50–2500 Hz. The aim of this study was to find out how the measurement uncertainty of the suggested single-number quantity, impact sound reduction index R_{impact}, differs from the measurement uncertainty of the current single-number quantity, weighted normalized impact sound pressure level $L'_{\mathrm{n,w}}$ defined at traditional frequency range 100–3150 Hz. The uncertainties of the indicator $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$ were calculated, too. Another aim was to study the uncertainties of the 1/3-octave band values of the normalized impact sound pressure levels L'_{n}. The measurement uncertainties were simulated with Monte Carlo method on the basis on 50 field measurements of concrete floors. It was shown that the measurement uncertainty of the single-number quantities depends on the shape of the impact sound spectrum and hence on the floor type. The measurement uncertainty of 1/3-octave band values does not depend on the floor type, which means that the uncertainty of the single number quantities is connected with the impact sound pressure levels that determine the value of the single-number quantities. The measurement uncertainties of both the 1/3-octave band values and the single-number quantities rise when the 1/3-octave bands 50, 63 and 80 Hz are included in the rating, but the change remains so small that it does not prevent the measurements at the enlarged frequency range. However, if some alternative reference spectrum or reference curve will be used in calculation of a SNQ, the measurement uncertainty of that SNQ will differ from the present SNQs, which should be taken into account when alternative reference spectra are used.

PACS: 43.55.-n

Keywords: building acoustics, impact sound insulation, uncertainty, standardization

1. Introduction

The measurement methods and definitions of indicators for impact sound insulation of intermediate floors have been developed during a period extending from the 1930's to the 1960's. [e.g. 1–9] The single-number quantities (SNQ) for the rating of impact sound insulation have been determined on the basis of sound pressure levels produced by the standardized tapping machine at 1/3-octave bands from 100 Hz to 3150 Hz. The frequency range to be measured was chosen to begin at the centre frequency band of 100 Hz because of the assumed decreasing accuracy at lower frequencies. [10]

It has long been recognized, that in many cases the walking sounds at frequency bands below 100 Hz may have a remarkable effect on the people's subjective evaluation of floors. [11–19] Since the 1990's, the ISO standards defining the measurement and rating methods have allowed for enlarging the measured frequency range down to 50 Hz in both airborne and impact sound insulation measurements. [20–21] However, most countries have not included this possibility in their national building regulation. [22–23] The reason for this has apparently been the expected increase in measurement uncertainty due to the properties of the sound field. [22, 24, 25]

The ISO standard defining the indicator for impact sound insulation will be revised in the future. In the revision process, a new quantity, an impact sound reduction index R_{impact}, has been suggested by Scholl. [26–27] The use of the proposed impact sound reduction index in the rating of impact sound insulation means that the measured frequency range will change from 100…3150 Hz to 50…2500 Hz. Lowering the frequency range limit from 100 Hz to 50 Hz in airborne sound insulation has also been recommended. The suggested changes have raised an ongoing discussion on the accuracy of sound insulation measurements at the frequency bands below 100 Hz. [e.g. 28–30]

The measurement methods of sound insulation are based on an assumption of a diffuse sound field but the standard ISO 140-7 defining the measurement method states that in small rooms, no diffuse sound field can be expected below 400 Hz. [21] This frequency corresponds to the limit of diffuse and non-diffuse sound field calculated according to Schroeder and Kuttruff [32] in the case of an empty room having a volume of 30 m^3. A substantial number of bedrooms in dwellings are of this size. [24, 25, 33]

According to the current standards, the accuracy of the singe-number quantities is evaluated by determining the reproducibility and repeatability values. [34] This method, however, is quite laborious, especially when usual consultant work is considered. In some studies, the accuracy of the measurements has also been evaluated by determining standard deviations for the sound pressure levels and reverberation times at the 1/3-octave centre frequency bands. [35–38] However, the derivation of confidence intervals or other statistical measures for the single-number quantities becomes difficult because of the reference curve method used in calculation of the quantities. Therefore, the Monte Carlo method in simulation of the distribution and uncertainty of the SNQs has been used in earlier studies. Normally, some generalized standard deviations like those presented in standards for the 1/3-octave band quantities have been used in the simulations. [39–41]

In the literature, most attention has been paid to measurement uncertainty of airborne sound insulation at low frequencies in laboratory conditions. [24, 25, 28, 38–41]. When judging the acceptability of a construction in a building or sound insulation between dwellings, a field measurement in a certain building between certain spaces is finally determining. The acoustic characteristics of the rooms in field measurements are always different because of the varying shapes and volumes of the rooms. As the measurement uncertainty depends on them, an uncertainty evaluation based on standard deviations of measurands in one room is not exact when applied to another room. Thus, the measurement uncertainty should be studied on the basis of field measurements, too.

The aim of this study was to study the measurement uncertainties of SNQs for impact sound insulation on the basis of field measurements. It was determined whether the measurement uncertainty of the suggested SNQ, impact sound reduction index R_{impact} measured at the enlarged frequency range 50–2500 Hz, differs from the uncertainty of the current SNQ, weighted normalized impact sound pressure level $L'_{n,w}$ defined at the traditional frequency range of 100–3150 Hz. The uncertainties of the single-number quantity $L'_{n,w} + C_I$ were also calculated. Another aim was to study the uncertainties of the 1/3-octave band values, normalized impact sound pressure levels L'_n at center frequency bands from 50 to 3150 Hz. The study focused on measurement uncertainty of field measurements only and only results normalized to reference absorption area were studied. Only concrete floors of new multi-storey apartment buildings were considered.

2. Materials and methods

2.1 Measured structures

All measurements have been carried out in pre-cast concrete buildings which are the most usual multi-storey building types in Finland. These buildings have load-bearing concrete elements as separating walls and usually concrete sandwich panels as outer walls. Non-bearing separating walls inside the apartments are mostly lightweight walls with timber or steel frame. Bearing structures of intermediate floors are hollow core slab fields or cast concrete slabs. Measured floors include all typical Finnish floor structures of new apartment buildings. The measured floors have been put into five groups on the basis of floor covering as follows (fig. 1):

- floor type A: floor covering cushion vinyl, n = 11
- floor type B: floor covering multi-layer parquet with soft underlayment, n = 21
- floor type C: floor type B with suspended ceiling, n = 3
- floor type D: raised floor system with battens, n = 5
- floor type E: floating floor, n = 10

Within each floor type, there is variation as the bearing structure can be a hollow core slab or cast concrete slab and the mass of the slab varies as well. The mass of cast concrete slabs varied from 600 kg/m^2 to 750 kg/m^2. The mass of hollow core slabs were 380, 400 or 510 kg/m^2. The weighted reduction of impact sound pressure level ΔL_w of cushion vinyls and multi-layer parquets with soft underlayment has been 17–19 dB. The bearing structure of raised floors (type D) consists of steel or timber battens supporting a board structure on which the floor covering is installed. Within floor type E, the dynamic stiffness s’ of the resilient layer of floors varied from 8 to 20 MN/m^3 according to the information given by the construction site. The mass of the floating layer varied from 40 kg/m^2 to 200 kg/m^2.

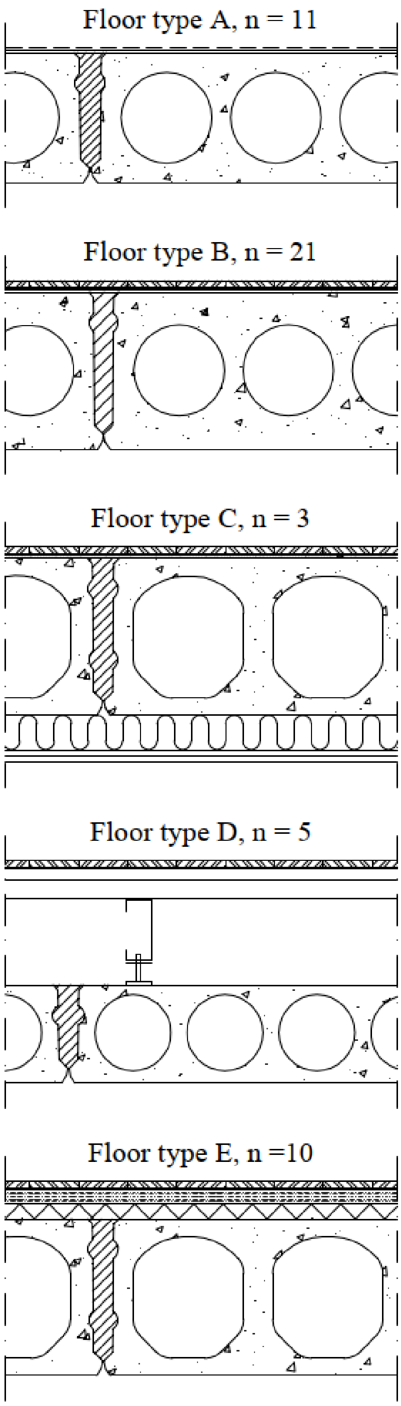

Figure 1. The studied floors were categorized in five groups. The bearing structures of the floors were either hollow core slabs as shown here or cast concrete slabs.

2.2 Measurements

In this study, only field measurement data was used. The measurements of normalized impact sound pressure levels L'_n were carried out according to the standard ISO 140-7. [21] Four tapping machine positions were used. Three random microphone positions per each tapping machine position were used. The averaging time has been 10 s at all frequency bands. The purpose of this study is to compare the measurement uncertainty of SNQs at different frequency ranges. In this case, the results are valid for the averaging time of 10 s.

Two corner positions of loudspeakers were used in the reverberation time measurements. The number of random microphone positions was three per each loudspeaker position. In each position, two decays were measured. The average reverberation time was calculated from twelve decays. The equipment used in sound pressure level and reverberation time measurements corresponds to the requirements of accuracy class 1.

All measurements described in the data have been carried out in unfurnished rooms. The volume V of the rooms varies between 24 and 117 m^3. The amount of measured floor structures was 50. Most of the rooms were small: 32 measurements were done in rooms having a volume smaller than 40 m^3.

2.3 Rating of measured floors

The weighted normalized impact sound pressure levels $L'_{n,w}$ of all floors were calculated according to the standard ISO 717-2. [20] The suggested impact sound reduction indices R_{impact} were calculated according to Scholl. [26] The calculation of impact sound reduction indices is based on measured normalized impact sound pressure levels L'_n. Both SNQs were calculated on the basis of a spatial average of 12 impact sound pressure level measurements and an average of 12 reverberation time measurements. The spectra of normalized impact sound pressure levels L'_n of all 50 floors are shown in figure 2.

According to the Finnish building regulations, the value of $L'_{n,w}$ should not exceed 53 dB. [42] All the measurement results presented in this study fulfill this requirement. Therefore, the uncertainty and deviation of the SNQs do assumingly not depend on failures in workmanship. The background noise levels in all rooms were 10 dB lower than the sound level of the tapping machine combined with background noise. Thus, no background noise correction was done.

The distributions of the weighted normalized impact sound pressure levels $L'_{n,w}$ and impact sound reduction indices R_{impact} are shown in figure 3. The suggested single-number quantity R_{impact} changes the ranking of the floors compared with the rating with $L'_{n,w}$.

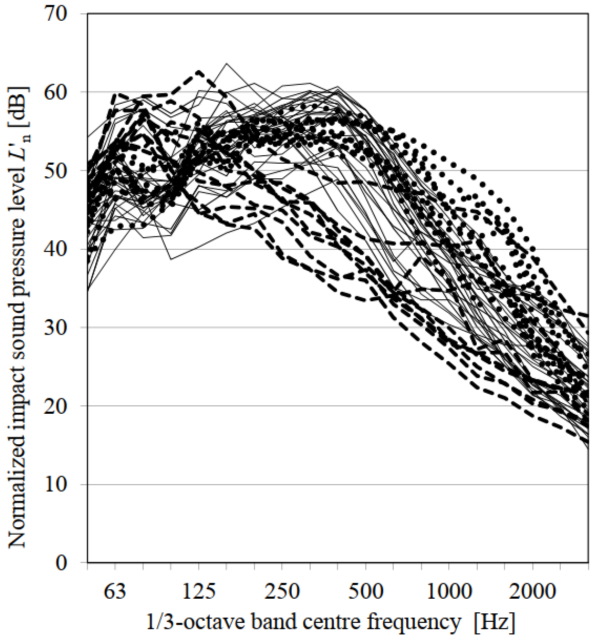

Figure 2. Impact sound pressure levels L'_n of all 50 measured floors. Dotted lines show sound spectra of floors A and dashed lines show sound spectra of floors E.

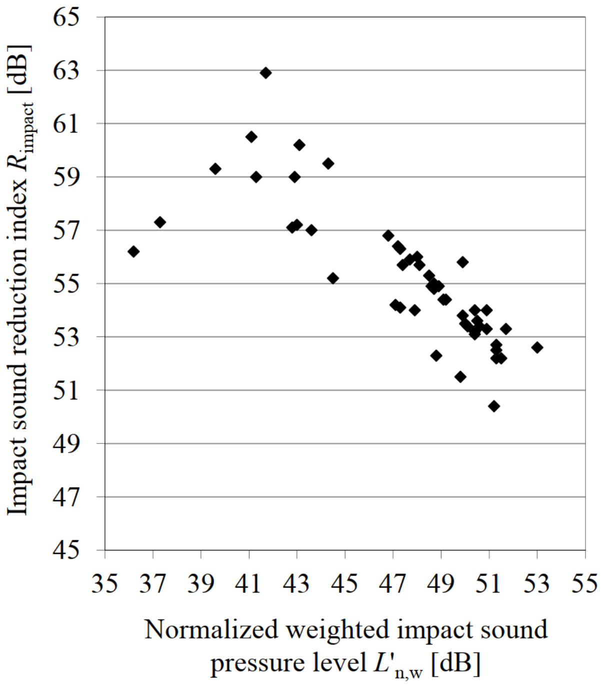

Figure 3. The rating of all 50 measured floors: impact sound reduction indices R_{impact} are given as a function of the weighted normalized impact sound pressure levels $L'_{n,w}$. Correlation between these two SNQ's is in the case of floor type E (floating floors) low because the measured impact sound pressure levels are highest below 100 Hz (see fig. 2).

2.4 Monte Carlo simulations

In acoustical research, the Monte Carlo method has been used since the 1950’s. [32, 43–44] The idea of the Monte Carlo method is that a value of a quantity is estimated on the basis of its variables receiving random values over a certain domain. The quantity is calculated by choosing one value for the variables over their domains. When the calculation is carried out repeatedly, a probability distribution of the quantity is achieved as a result. [45] The SNQ for judging the impact sound insulation of buildings, the weighted normalized impact sound pressure level $L'_{n,w}$, is determined with the reference curve method [20] which makes it difficult to derive statistical uncertainty estimates like confidence intervals. In these kinds of cases, a Monte Carlo simulation provides a useful method for estimating the deviation of the quantities.

The standard ISO 140-7 [21] requires that the minimum number of measurements of sound pressure levels is six so that the spatial average is a combination of four microphone and four tapping machine positions. In calculating the average of reverberation time, the minimum number of decays is also six. The average should be based on at least one loudspeaker position and three microphone positions. In each microphone position, two decays should be measured.

Instead of the minimum amount of sound pressure level measurements and decays, 12 reverberation time measurements and 12 impact sound pressure levels were done. Following the rules presented in the standard, 20 averages $T_{sim,j}$ of reverberation times and 486 spatial averages $L_{k,sim,j}$ of impact sound pressure levels per each measured structure could be calculated. In the Monte Carlo simulations presented below, all the values of the variables are results from field measurements instead of random values selected within the range of the measured variables.

From the combinations of reverberation times $T_{sim,j}$ and impact sound pressure levels $L_{k,sim,j}$, it is possible to calculate altogether 9720 combination curves $L_{n,sim,j}$ of normalized impact sound pressure levels and impact sound reduction indices $R_{i,sim,j}$. From each of the simulated curves, the simulated values for the single-number quantities $L'_{n,w}$, $L'_{n,w} + C_I$, $L'_{n,w} + C_{I,50\text{-}2500}$ and R_{impact} can be determined. The standard ISO 717-2 requires that the weighting with reference curve method is done by moving the reference curve in steps of 1 dB. [20] In order to achieve a more precise understanding of the uncertainty of the quantities, the work by Wittstock was followed: simulations were done by moving the reference curve in steps of 0,1 dB. [40] The impact sound reduction indices were also rounded to 0,1 dB.

2.5 Deviations of single-number quantities

The uncertainty of the SNQs was evaluated as probability distributions of the deviations D between the single simulated values $X_{sim,j}$ and the mean value $X_{sim,avg}$ of the simulated SNQs. In this way, the following probability distributions of deviations D were calculated:

$$D_1 = L'_{n,w,sim,j} - L'_{n,w,sim,avg} \tag{1}$$

$$D_2 = (L'_{n,w} + C_I)_{sim,j} - (L'_{n,w} + C_I)_{sim,avg} \quad (2)$$

$$D_3 = (L'_{n,w} + C_{I,50\text{-}2500})_{sim,j} - (L'_{n,w} + C_{I,50\text{-}2500})_{sim,avg} \quad (3)$$

$$D_4 = R_{impact,sim,j} - R_{impact,sim,avg} \quad (4)$$

An example of the probability distributions of the deviations D_1–D_4 is shown in figure 4. From each of the 50 field measurements, the corresponding probability distributions have been determined. In below, the results for the deviation D_3 ($L'_{n,w} + C_{I,50\text{-}2500}$) will not be studied further as the single-number quantity $L'_{n,w} + C_{I,50\text{-}2500}$ corresponds reversely to impact sound reduction index R_{impact}. [26–27] The only difference between the probability distributions of D_3 and D_4 (R_{impact}) is that the probability distribution of D_3 is reversed over the zero position which can be seen in figure 4.

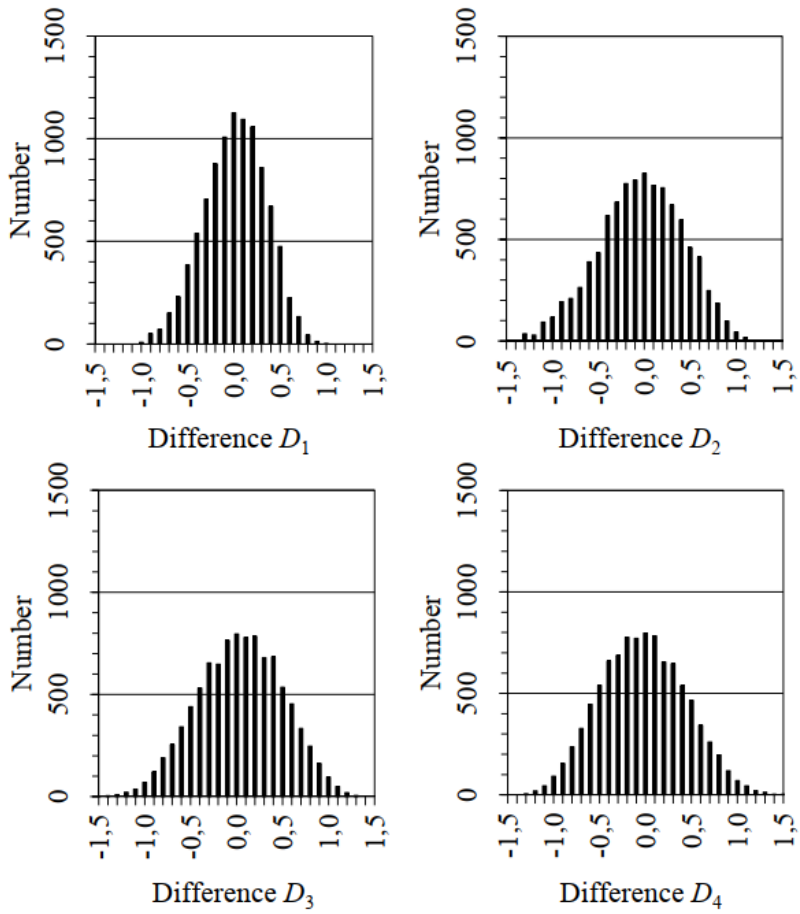

Figure 4. Deviations $D_1 \ldots D_4$ [dB] of the differences between simulated values and the averages of the SNQs. The deviations are based on the field measurement of a floor consisting of a floating floor (leveling compound 35 mm as a floating layer and mineral wool 40 mm) and a cast concrete slab of 240 mm. Small differences in the reverse symmetry of the distributions of D_3 and D_4 are evidently due to rounding in the calculation of the SNQ's.

3. Results

3.1 Normalized impact sound pressure levels

The standard deviations of the simulated normalized impact sound pressure levels $L'_{n,sim,j}$ are shown in figure 5. Each point in the figure represents the standard deviation in a single measurement at a certain centre frequency. Each standard deviation represented by a dot in figure 5 has been calculated from 9720 simulated values of the normalized impact sound pressure level. The standard deviations of the simulated impact sound reduction indices $R_{i,sim,j}$ have not been shown because they are equal to those of $L'_{n,sim,j}$.

Figure 2 describes the spectra of normalized impact sound pressure levels for floor types A and E separated from spectra of other floors. Corresponding standard deviations of simulated values $L'_{n,sim,j}$ of floor types A and E have been shown in figure 6. These floor types have different impact sound spectra but the amount of measured floors of these types were almost equal, 11 (type A) and 10 (type E).

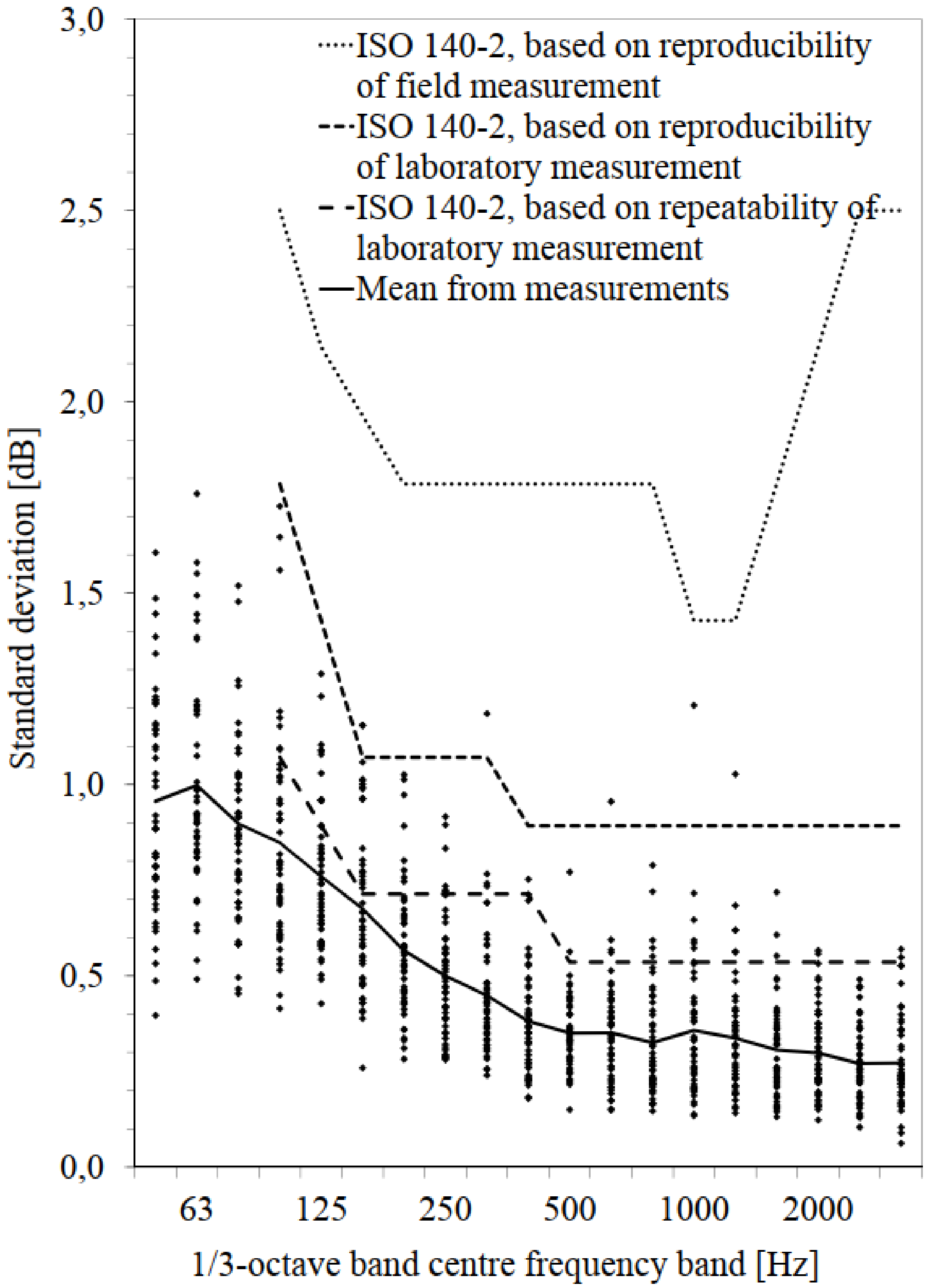

Figure 5. Standard deviations of simulated normalized impact sound pressure levels $L'_{n,sim,j}$ in all 50 field measurements compared with standard deviations based on repeatability and reproducibility values given in the standard ISO 140-2.

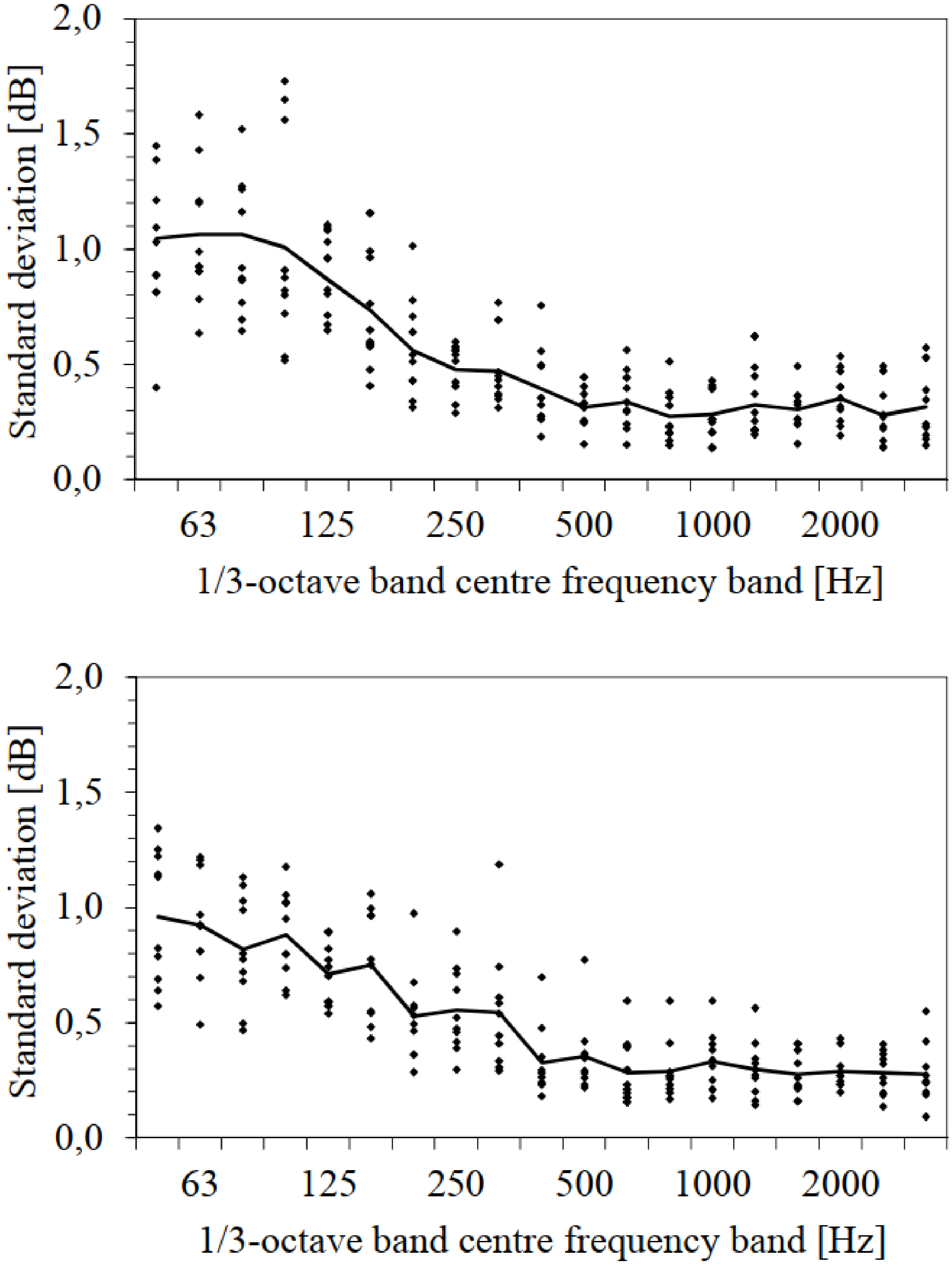

Figure 6. Standard deviations of simulated normalized impact sound pressure level $L'_{n,sim,j}$ of floor type A (above) and E (below). Averages of standard deviations are shown with the continuous line.

3.2 Single-number quantities

The probability distributions for deviations D_1 ($L'_{n,w}$), D_2 ($L'_{n,w} + C_I$) and D_4 (R_{impact}) between the simulated values of SNQs and their averages have been presented in figures 7–9. In the figures, deviations in all 50 field measurements and deviations in measurements of the floor types A–E have been presented separately. The standard deviations of D_1, D_2 and D_4 have been shown in figure 10 for each of the 50 measured floors separately.

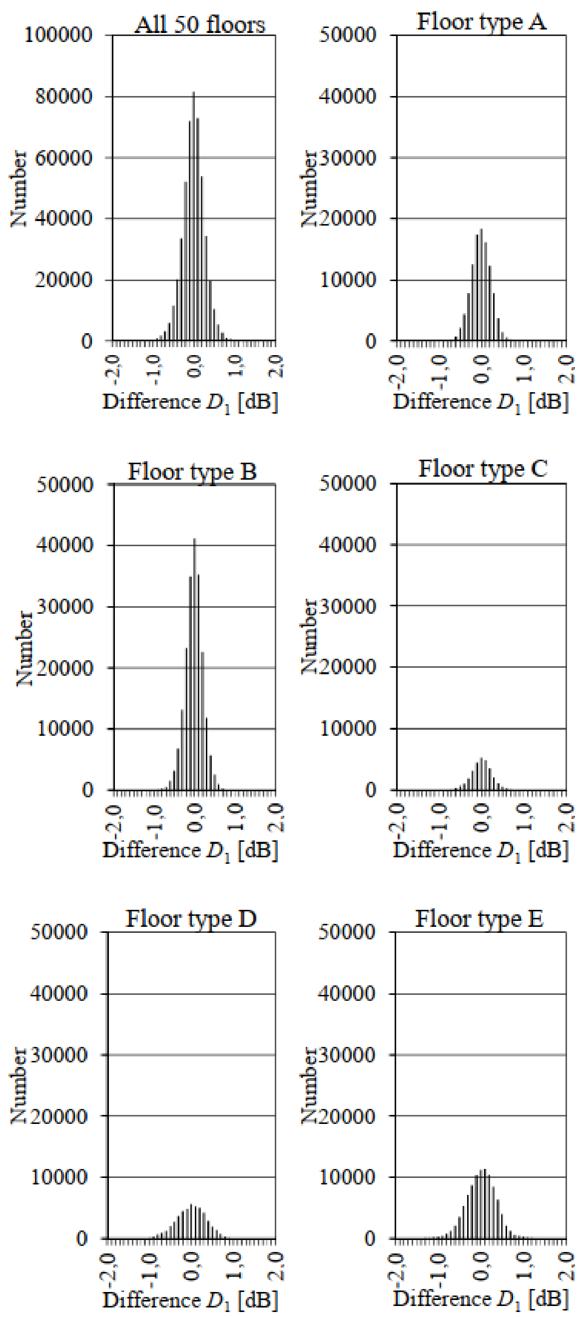

Figure 7. The probability distributions of deviations D_1 ($L'_{n,w}$) for all 50 field measurements and for the five floor types A–E separately.

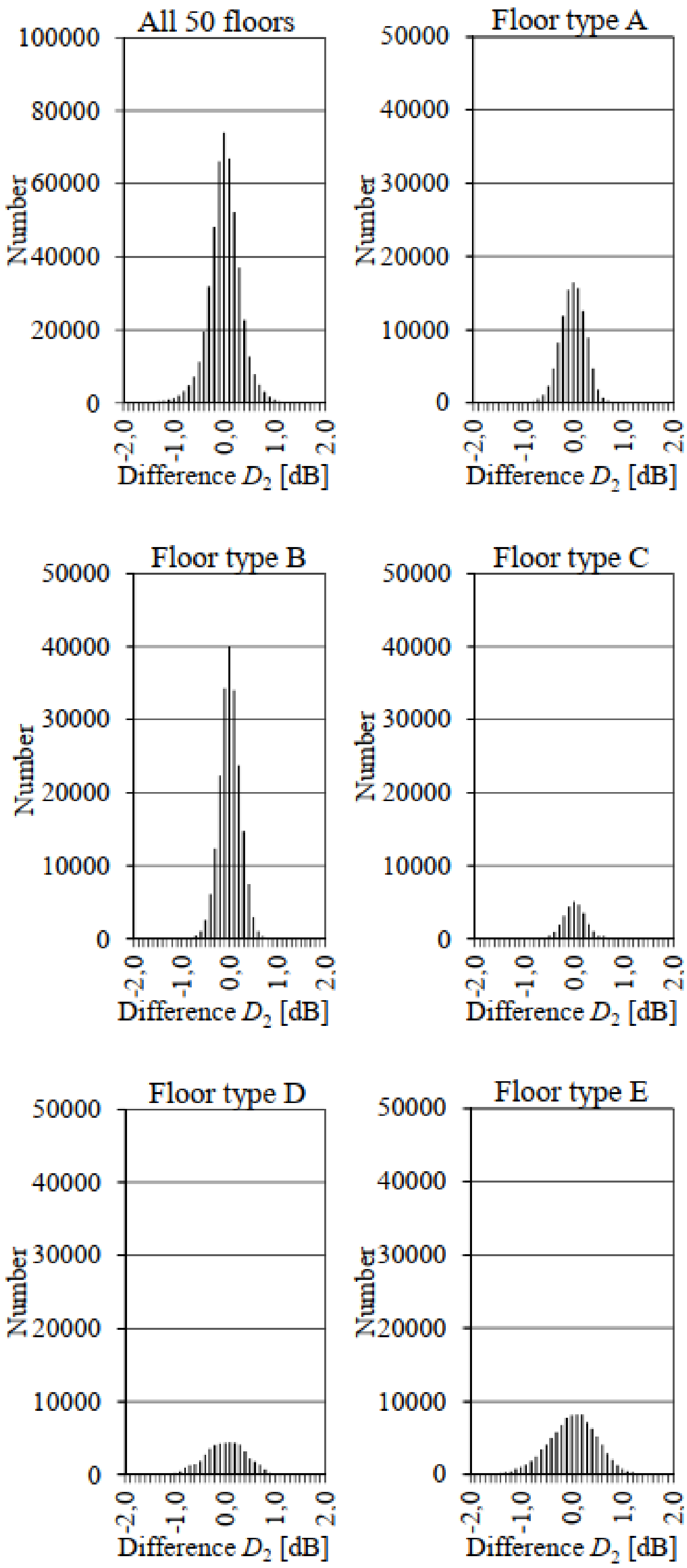

Figure 8. The probability distributions of deviations D_2 ($L'_{n,w} + C_I$) for all 50 field measurements and for the five floor types A–E separately.

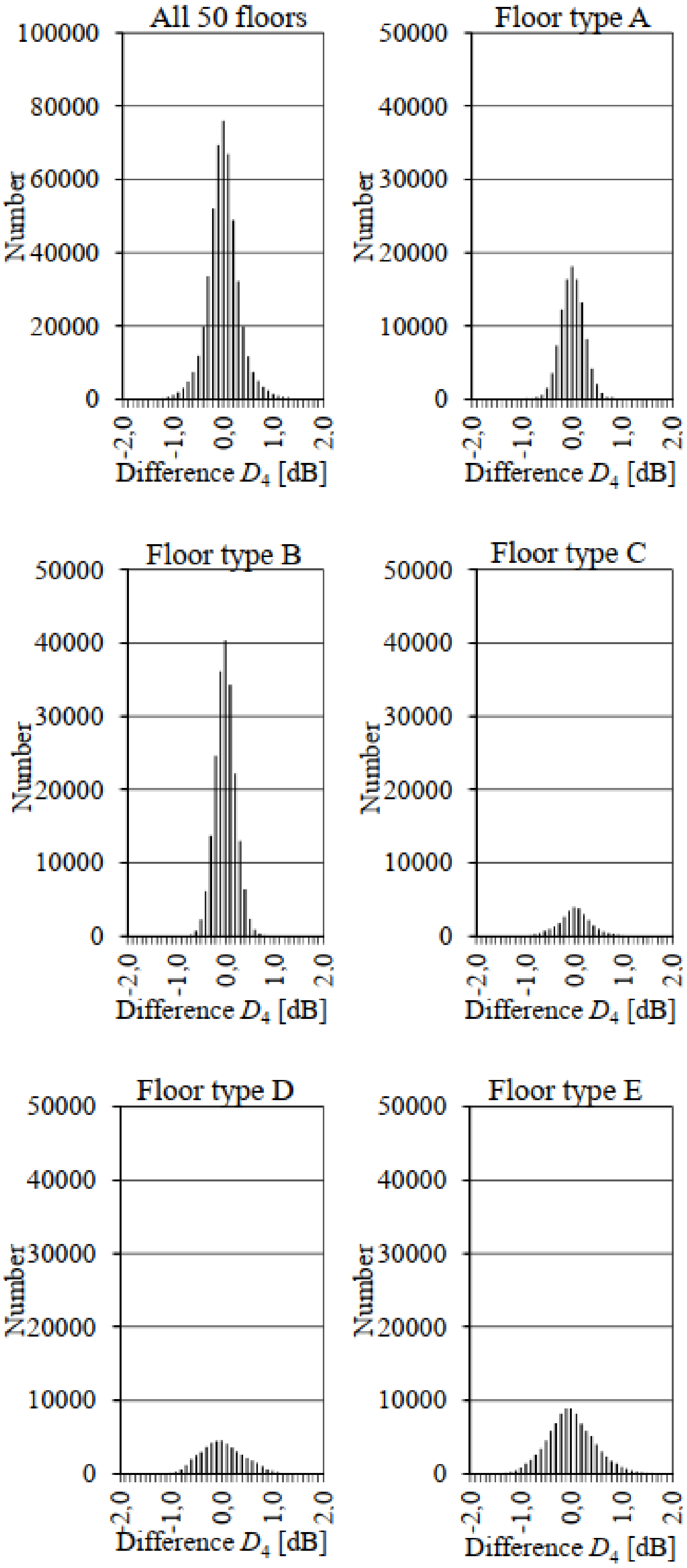

Figure 9. The probability distributions of deviations D_4 (R_{impact}) for all 50 field measurements and for the five floor types A–E separately.

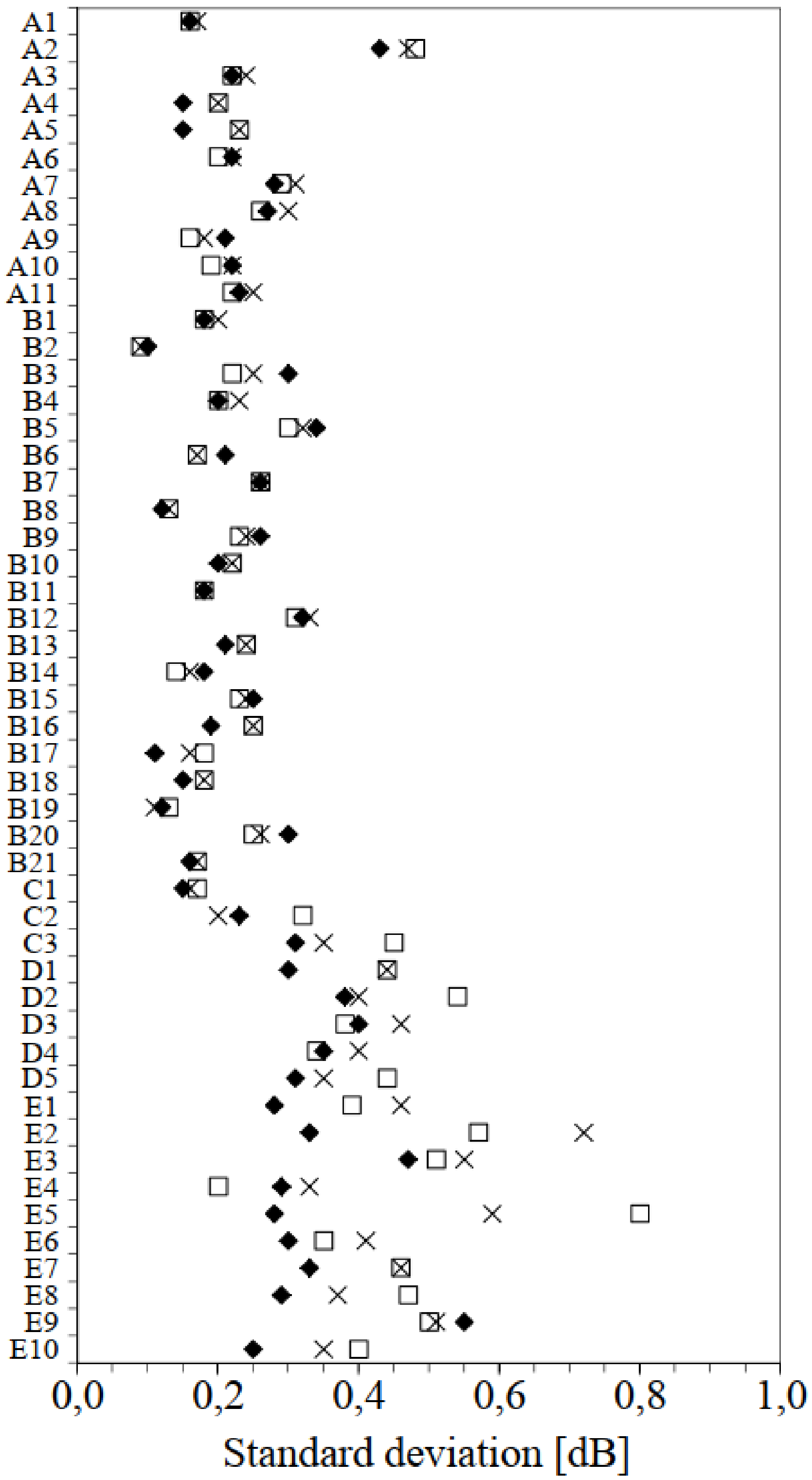

Figure 10. The standard deviations of differences D_1 (♦) for $L'_{n,w}$, D_2 (×) for $L'_{n,w} + C_I$ and D_4 (□) for R_{impact} of simulated SNQs of each measured floor A1…E10.

4. Discussion

4.1 Normalized impact sound pressure levels

As can be expected on the basis of earlier studies [35–38], the standard deviations of the simulated values of normalized impact sound pressure levels $L'_{n,sim,j}$ increase as the frequency decreases. The increase begins at the centre frequency of 400 Hz (fig. 5 and 6). The maximum value of the average is 1,0 dB at 63 Hz. Compared with the average standard deviation at 100 Hz, the increase is 0,15 dB. In single field measurements, the maxima of standard deviations occurred at centre frequency bands 50, 63, 80 and 100 Hz. The maximum standard deviations were 1,6, 1,8, 1,5 and 1,7 dB, correspondingly.

The current standard ISO 140-2 [34] defines repeatability and reproducibility values for the evaluation of uncertainties of results of sound insulation measurements. The repeatability value of a quantity represents the uncertainty in within-laboratory tests and the reproducibility value includes the repeatability value and between-laboratory uncertainties. The standard deviations of the measurands can be calculated from the repeatability and reproducibility values. For the normalized impact sound pressure levels, the standard gives both repeatability and reproducibility values for laboratory measurements and reproducibility values for field measurements. The standard deviations based on these values are shown in figure 5.

In the present standard ISO 140-2, the repeatability and reproducibility values are given to the centre frequency band of 100 Hz. [34] No standardized values for lower frequency bands are known, but at the lowest frequency bands, the standard gives repeatability and reproducibility values that rise rapidly at 160 Hz in the case of laboratory measurements. Standard deviations based on reproducibility values in field measurements start rising at 200 Hz and the rise increases at 125 Hz suggesting an exponential rise at lower frequency bands. Judging from this, one could conclude that the standard deviations grow linearly or even exponentially below 100 Hz. However, this kind of rapid increase cannot be seen in the standard deviations of the simulated values of $L'_{n,sim,j}$ (fig. 5 and 6). Corresponding result could also be expected on the theoretical basis presented in [46].

4.2 Single-number quantities

The averages of standard deviations of simulated normalized impact sound pressure levels $L'_{n,sim,j}$ were around 1 dB at the lowest centre frequency bands and 0,5 dB or less at frequency bands higher than 250 Hz. The standard deviations of SNQs are in most cases smaller than the standard deviations of simulated normalized impact sound pressure levels $L'_{n,sim,j}$ (fig. 5 and 10).

The largest standard deviations of simulated SNQs are 0,8 dB. The standard deviations of D_1 ($L'_{n,w}$), D_2 ($L'_{n,w} + C_I$) and D_4 (R_{impact}) tend to be larger for floor types D and E than for A, B and C. In the cases of floor types A, B and C, the correlation coefficient r between differences D_1 and D_2, D_1 and D_4 and D_2 and D_4 are 0,92, 0,83 and 0,83, respectively. This means that the measurement uncertainty of all SNQs is almost equal in the case of floors A, B and C. For floors types D and E, the corresponding correlation coefficients are 0,30, 0,12 and 0,66. In this case, the measurement uncertainty of single-number quantity $L'_{n,w} + C_I$ equals best the measurement uncertainty of single-number quantity R_{impact}. Figure 10 indicates that in some cases, the standard deviation D_2 ($L'_{n,w} + C_I$) is larger than the standard deviation D_4 (R_{impact}). This can be interpreted so that the standard deviations of D_i do not depend on the measured frequency range only, but also on the spectrum of of L'_n or R_i.

Rating the floor by single-number quantities $L'_{n,w} + C_{I,50\text{-}2500}$ or R_{impact} may change the rating of the floor more than 10 dB (fig. 3). The change in the measurement uncertainty at the enlarged frequency range remains evidently much lower than the change in the rating of floors. From this point of view it is not justified to put the increased measurement uncertainty of SNQs at enlarged frequency range under question. This result differs from the conclusions of a study dealing with measurement uncertainty evaluation of the SNQs for airborne sound insulation. [28]

4.3 Dependence of measurement uncertainty on floor type

Figures 7–10 indicate that the measurement uncertainty depends on floor type. This raises a question if the increase in standard deviations of D_i of the SNQs in the case of floor types D and E depend on the unevenness of the floor structure and failures in workmanship rather than on the acoustical properties and sound spectra. There are more structural layers in floor types D and E than in types A and B, which means that there are also more failure sources in workmanship. In literature, differing measurement uncertainties of SNQs for airborne and impact sound insulation have been reported in cases when the building systems and structural types of floors and walls vary. The reported reason for the differences has been failures in workmanship. [47–50]

Figure 2 describes the spectra of normalized impact sound pressure levels L'_n of floor types A and E. The normalized impact sound pressure levels of floors A are at a maximum around centre frequency bands 315 and 400 Hz. In the case of floor types E, the maxima lie at a frequency range below 200 Hz. This difference, however, does not affect the standard deviations of the simulated normalized impact sound pressure levels $L'_{n,sim,j}$, but the standard deviations behave quite similarly in both cases (fig. 6).

The results in figures 6 and 10 show that the measurement uncertainty depending on the sound field is not affected by the structural properties of the floor type like unevenness of the structure or failures in workmanship. Instead, the measurement uncertainty of the SNQs depends on the frequency range which in the rating determines the position of the reference curve or which contains the maximum sound pressure levels. The rating of floors A is determined by the frequencies around 315–400 Hz. As the standard deviations of simulated normalized impact sound pressure levels $L'_{n,sim,j}$ is at that range lower than at frequency range below 200 Hz, the standard deviations of simulated SNQs of floors A become smaller than those of floors E as the rating of these floors is determined by impact sound pressure levels below 200 Hz.

The result raises a question whether it is possible at all to give a generalized uncertainty value for building acoustical quantities or should that be done for each single measurement every time when the quantity is measured. If an allowable uncertainty limit will be set, that should be based on the floors which are rated on the basis of impact sound pressure levels at low frequency range, also in the case when measured frequency range would not be enlarged below 100 Hz. An alternative to this could be based on Monte Carlo simulation if more than minimum number of patting machine and microphone positions in sound pressure level measurements and more than minimum number of decays in reverberation time measurements would be used.

The definition of the suggested new single-number quantity R_{impact} includes the use of a reference spectrum. In the suggestion, an idealized spectrum of the tapping machine is used. The calculation method also allows for the use of an alternative reference spectrum. [26] If some alternative reference spectrum will be used, it will also change the measurement uncertainty of SNQ, which should be taken into account.

5. Conclusions

The measurement uncertainty of a suggested single-number quantity R_{impact} for rating of impact sound insulation of floors as well as measurement uncertainty of current single-number quantities $L'_{\mathrm{n,w}}$ and $L'_{\mathrm{n,w}} + C_{\mathrm{I}}$ were simulated by the Monte Carlo method on the basis of field measurement of 50 concrete floors. It was shown that the measurement uncertainty of the SNQs depends on the impact sound spectrum of the floor type. The measurement uncertainty of 1/3-octave band values does not depend on the floor type, which means that the uncertainty of the single number quantities is connected with the impact sound pressure levels that determine the value of the SNQs. The measurement uncertainties of both the 1/3-octave band values and the SNQs rise when the 1/3-octave bands 50, 63 and 80 Hz are included in the rating. This change, however, remains insignificant when compared with the change in floor rating. If some alternative reference spectrum or reference curve will be used in calculation of a SNQ, the measurement uncertainty of that SNQ will differ from the present SNQs, which should be taken into account.

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PUBLICATION V

Uncertainty of alternative single-number quantities for rating of impact sound insulation

Mikko Kylliäinen, Ville Kovalainen, Jesse Lietzén & Valtteri Hongisto

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Uncertainty of alternative single-number quantities for rating of impact sound insulation

Mikko Kylliäinen
Tampere University of Technology, Department of Civil Engineering, Tampere, Finland
Ville Kovalainen
Tampere University of Technology, Department of Civil Engineering, Tampere, Finland
Jesse Lietzén
A-Insinöörit Suunnittelu Oy, Acoustical Engineering Unit, Tampere, Finland
Valtteri Hongisto
Finnish Institute of Occupational Health, Indoor Environment Laboratory, Turku, Finland

Summary
The ISO standard 717-2 defining the single-number quantities for rating of impact sound insulation will be revised in the future. In the revision process, a new quantity, impact sound reduction index R_{impact}, has been suggested by Scholl. The use of this new single-number quantity requires a reference spectrum. The calculation method of R_{impact} also enables the use of alternative reference spectra. So far, such alternative spectra have not been presented. However, alternative reference curves have been suggested in the literature since the 1960s. Our earlier studies have shown that the impact sound spectrum of floor excited by the tapping machine has an effect on the measurement uncertainty of the single-number quantities. The aim of this study was to find out how the shape of the reference curve affects the uncertainty. Measurements were done with nine floor coverings on the same concrete slab. The reference curves used in calculation of the single-number quantities have been presented by Fasold (1965), Gerretsen (1976), Bodlund (1985) and Hagberg (2010). In addition, the single number quantities $L'_{\text{n,w}}$ and $L'_{\text{n,w}} + C_{\text{I}}$ and their uncertainties were calculated. In calculation of the uncertainties, Monte Carlo method was used. It could be shown, that the shape of the reference curve and its frequency range have a remarkable effect on the uncertainty of the single-number quantities.

PACS 43.55.+p

1. Introduction

The ISO standard 717-2 [1] defining the single-number quantities (SNQ) for rating of impact sound insulation will be revised in the future. In the revision process, a new quantity, impact sound reduction index R_{impact}, has been suggested by Scholl. The calculation of this new single-number quantity requires a reference spectrum. [2–3]

There is recent evidence indicating that the suggested SNQ, R_{impact} corresponding to the sum $L'_{\text{n,w}} + C_{\text{I,50-2500}}$, does not rank the floors in the same order as the indicators based on loudness levels or A-weighted sound levels of walking. [4] Similar results for correlation between $L'_{\text{n,w}}$ and objective judging of walking sounds have been obtained already long by many authors. [5–8] On this basis, it can be concluded that some other reference spectrum is needed to improve the correlation.

The calculation method of R_{impact} enables the use of alternative reference spectra. [9] Our earlier study [10] has shown that the impact sound spectra resulting from excitation of different floor structures by the tapping machine have an effect on the measurement uncertainty of the single-number quantities. From that result, it is possible to assume that an alternative reference spectrum or reference curve used in calculation of an SNQ will also change the uncertainty of the SNQ.

Alternative reference spectra for calculation of R_{impact} have not been presented yet even though a method for deriving such spectra has been given in reference [9]. However, alternative reference curves have been suggested in the literature since the 1960's. [11–14] The aim of this study was to find out how the shape and frequency range of the reference curve affects the uncertainty of SNQs meant for rating of the impact sound insulation.

2. Materials and methods

2.1. Measurements

Impact sound insulation measurements were carried out at the Upofloor laboratory in Nokia, Finland. The measurements were done according to the field measurement standard ISO 140-7 [15]. There were four fixed tapping machine positions and the sound produced by the tapping machine was measured in four fixed microphone positions. Two corner positions of loudspeakers were used in the reverberation time measurements. The number of fixed microphone positions was four per each loudspeaker position. In each position, two decays were measured.

The bearing structure of the floor was 265 mm thick concrete hollow core slab (400 kg/m^2). Nine different floor coverings were used. All the floor coverings were installed on the same position on the bearing hollow core slab. The size of the floor covering was 3,0 x 4,0 m^2. The layers of the floor coverings have been shown in table I. The floor coverings were installed as carefully as possible in order to avoid the effects of workmanship on the deviations of measured sound pressure levels.

Table I. Structural layers of the floor coverings denoted with letter F and a number.

Denotation	Floor covering
F1	No covering
F2	Cushion vinyl ΔL_w = 2 dB
F3	Cushion vinyl ΔL_w = 21 dB
F4	Multilayer parquet 14 mm Soft underlayment ΔL_w = 20 dB
F5	Wall-to-wall carpet ΔL_w = 21 dB
F6	Wall-to-wall carpet ΔL_w = 37 dB
F7	Multilayer parquet 14 mm Soft underlayment 2 x plasterboard 15 mm Mineral wool 13 mm, s' = 12 MN/m^3
F8	Multilayer parquet 14 mm Soft underlayment 2 x plasterboard 15 mm Mineral wool 50 mm, s' = 8,9 MN/m^3
F9	Multilayer parquet 14 mm Soft underlayment 4 x plasterboard 15 mm Mineral wool 50 mm s' = 8,9 MN/m^3

2.2. Alternative reference curves

Alternatives to the ISO reference curve for calculation of the single-number quantities have been presented since the 1960s by Fasold [11], Gerretsen [12], Bodlund [13] and Hagberg [14]. The SNQs calculated on the basis of these reference curves are denoted by $L'_{n,Fas}$, $L'_{n,Ger}$, $L'_{n,Bod}$ and $L'_{n,Hag}$, correspondingly. As the SNQ presented by Fasold can be calculated from the normalized impact sound pressure levels L'_n at frequency range 100–3150 Hz or 50–3150 Hz, lower limits of the frequency ranges have been shown in the case of SNQs according to Fasold. SNQs $L'_{n,w}$, $L'_{n,w} + C_I$ and R_{impact} were also calculated. [1–2]

The reference curves presented by the above mentioned authors have been shown in figure 1. In the calculation of each SNQ, the maximum allowable sum of the unfavourable deviations from the reference curve has been 32 dB as it has been shown that the sum does not have remarkable effects on the subjective rating of the floors. [13] In order to achieve a more precise understanding of the uncertainty of the SNQs, the work by Wittstock [16] was followed and all SNQs were defined by moving the reference curve in steps of 0,1 dB.

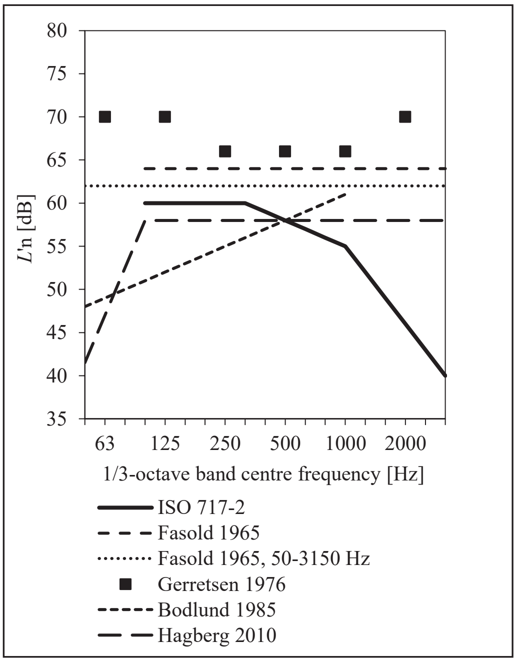

Figure 1. Alternative reference curves used in calculation of SNQs.

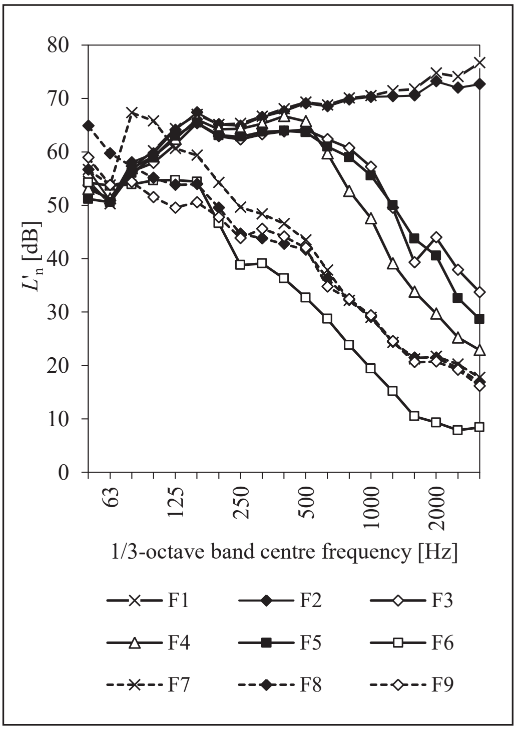

Figure 2. Normalized impact sound pressure levels L'_n produced by the nine floor coverings.

The measured spectra of the normalized impact sound pressure levels L'_n are shown in figure 2. The SNQs calculated from the normalized impacts sound pressure levels on the basis of different reference curves are presented in Table II.

2.3. Monte Carlo simulations

The standard ISO 140-7 defines that the minimum number of measurements of impact sound pressure levels is six so that the spatial average of sound pressure levels is a combination of four microphone and four tapping machine positions. In calculating the reverberation time, the minimum number of decays is also six. The average should be based on at least one loudspeaker position and three microphone positions. In each microphone position, two decays should be measured. [15]

Instead of the minimum amount of sound pressure level measurements and decays, 16 reverberation time measurements and 16 impact sound pressure levels were done. Following the rules presented in the standard, 56 averages of reverberation times and 1 656 spatial averages of impact sound pressure levels per each measured floor covering could be calculated. The SNQs were then calculated by choosing one average for the reverberation time and one average for the spatial average of impact sound pressure level. As a result, 92 736 normalized impact sound spectra could be simulated. These Monte Carlo simulations [17] were thus carried out so that all the values of the variables were results from measurements instead of random values selected within the range of the measured variables.

The uncertainties of the SNQs were evaluated as probability distributions of the differences D_i between the single simulated values X_j and the mean value X_{avg} of the simulated SNQs:

Table II. Calculated single-number quantities of the nine measured floor structures.

Floor	$L'_{n,w}$	$L'_{n,w} + C_I$	R_{impact}	$L'_{n,Fas,100}$	$L'_{n,Fas,50}$	$L'_{n,Ger}$	$L'_{n,Bod}$	$L'_{n,Hag}$
F1	79,9 dB	66,7 dB	37,3 dB	68,4 dB	68,4 dB	66,4 dB	66,0 dB	68,7 dB
F2	77,7 dB	65,8 dB	38,2 dB	67,3 dB	67,3 dB	65,6 dB	65,9 dB	67,8 dB
F3	58,7 dB	58,0 dB	45,9 dB	59,4 dB	59,4 dB	58,4 dB	62,6 dB	60,7 dB
F4	59,1 dB	59,0 dB	44,9 dB	60,4 dB	60,4 dB	59,8 dB	63,9 dB	61,8 dB
F5	58,5 dB	58,0 dB	45,9 dB	59,4 dB	59,4 dB	58,6 dB	62,8 dB	60,5 dB
F6	42,7 dB	44,7 dB	56,7 dB	44,7 dB	49,0 dB	41,9 dB	56,5 dB	54,5 dB
F7	50,1 dB	53,0 dB	48,1 dB	52,1 dB	55,6 dB	50,3 dB	62,8 dB	61,2 dB
F8	43,2 dB	45,0 dB	51,6 dB	45,2 dB	52,2 dB	43,6 dB	59,8 dB	61,0 dB
F9	41,3 dB	42,1 dB	56,4 dB	43,0 dB	47,8 dB	41,5 dB	55,3 dB	56,1 dB

$$D_{\mathrm{i}} = X_{\mathrm{j}} - X_{\mathrm{i,avg}} \qquad (1)$$

Letter i denotes here the studied single-number quantities, for example D_{Ger} denotes the difference between simulated values of $L'_{\mathrm{n,\,Ger,j}}$ and $L'_{\mathrm{n,\,Ger,avg}}$, the mean value of all the simulated values.

3. Results

From each simulated spectra of L'_{n} of the nine floor structures, the eight SNQs and differences D_{i} were calculated. The calculated 92 736 differences form a probability distribution (fig. 3).

Standard deviations of the differences D_{i} of all SNQs are described in figure 4. In the case of floors F1…F5, the standard deviations of D_{i} are below 0,45 dB for all SNQs. In this case, differences between the standard deviations of D_{i} of all SNQs are within 0,3 dB.

In the case of floors F6…F9, the standard deviations of D_{i} rise and the differences between the standard deviations D_{i} based on different SNQs also become larger. The largest difference between the standard deviations occurs in the case of floor F8.

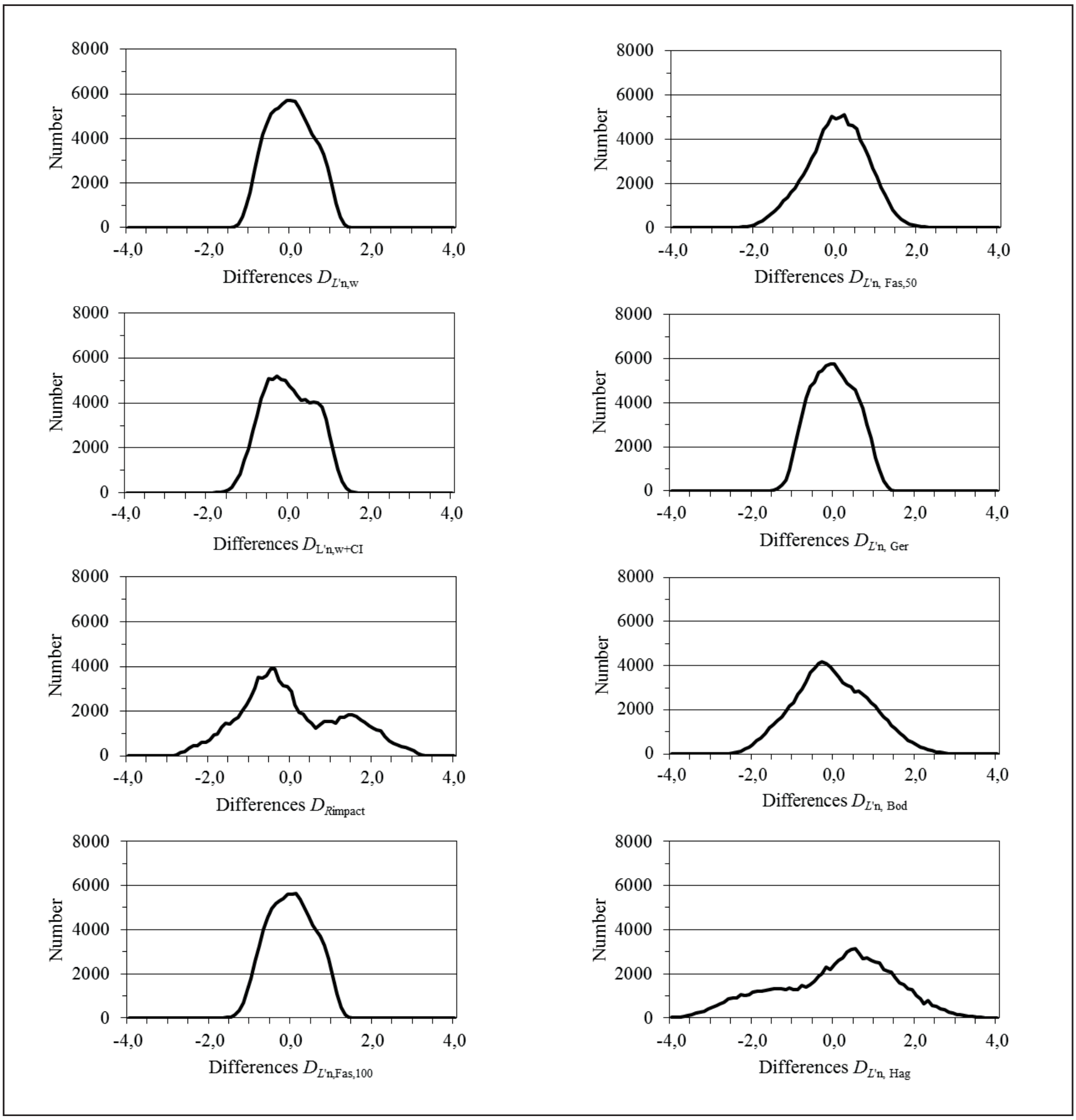

Figure 3. Probability distributions D_{i} in the case of floor F8. The number of simulated values is shown at y-axis.

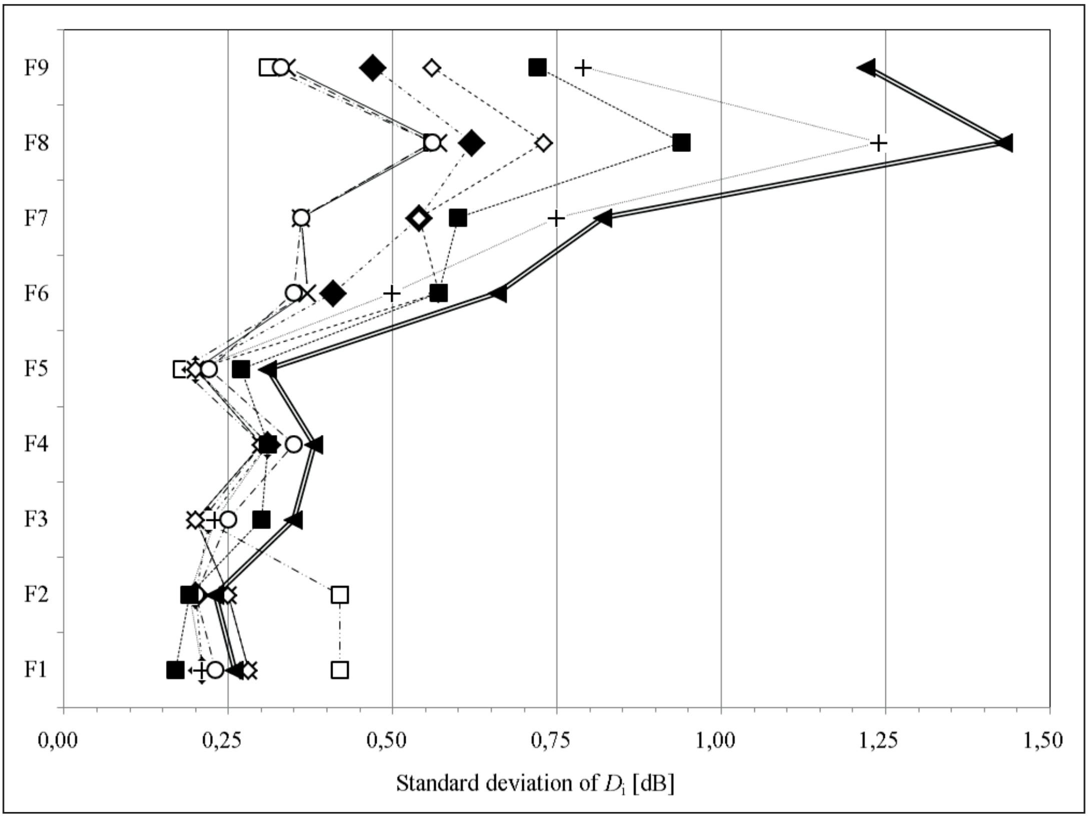

Figure 4. Standard deviations of D_i for all SNQs and all floors F1…F8. Markings: □ $D_{L'n,w}$, ♦ $D_{L'n,w+CI}$, + $D_{R\text{impact}}$, × $D_{L'n,Fas,100}$, ◊ $D_{L'n,Fas,50}$, ○ $D_{L'n,Ger}$, ■ $D_{L'n,Bod}$, ◀ $D_{L'n,Hag}$.

4. Discussion

In the case of floors F6…F9, the positions of the reference curves are determined by the values of L'_n at 1/3-octave bands below 200 Hz (fig. 2). It is known on empirical [10] and theoretical [18] basis that standard deviations of normalized impact sound pressure levels $L'_{n,w}$ measured at 1/3-octave bands rise at lower frequencies. Earlier results have also confirmed that the spectrum of L'_n affects the measurement uncertainty of SNQ. [10] These phenomena explain partly the rise of standard deviations of D_i of each SNQ which is described in figure 4.

The rising differences between the standard deviations D_i cannot, however, be explained by the earlier results only. On the basis of the shapes of the reference curves, impact sound spectra of the floors and calculated SNQs, it can be concluded that the shape of the reference curve also affects significantly the uncertainty of the SNQs. The more the reference curve weights the low frequencies in the rating of floors, the larger the standard deviations of D_i become.

The standard deviations of D_i are largest in the case of Hagberg's reference curve, which has the steepest slope at the frequency range below 100 Hz. In the case of floor F8, standard deviation of $D_{L'n,Hag}$ is nearly 0,9 dB larger than standard deviation of $D_{L'n,w}$ and $D_{L'n,Ger}$. Figure 3 also shows how the probability distributions are the flatter the more the SNQ weights the low frequency range.

The difference between weakest and best ratings of the nine floors was 38,6 dB when rated with $L'_{n,w}$. The corresponding difference was only 10,7 dB, when rated with $L'_{n,Bod}$. The use of different SNQ's changes the rating of a floor and the ranking order of the floors as well. The changes in rating and ranking order of floors are much larger than the changes in measurement uncertainties when the low frequency range is taken into account, even when the rating method weights strictly the low frequency range. This means that the uncertainty questions at low frequencies are not necessarily as important as they have earlier thought to be. [19]

The bearing structure of the floors was in this study a concrete hollow core slab. The results presented here are thus valid for concrete structures only. The effect of workmanship might be more significant in the case of wood structures as has been reported in the reference [20].

5. Conclusions

Single-number quantities for rating of impact sound insulation of nine different floors were simulated with Monte Carlo method. The results confirmed an earlier conclusion that the uncertainty of different SNQs depends on the impact sound spectrum of the floor. In addition, it could also be shown that the shape of the reference curve and its frequency range have a remarkable effect on the uncertainty of the single-number quantities.

Uncertainty of an SNQ thus depends both on the impact sound spectrum of the floor and on the shape and frequency range of the reference curve or reference spectrum. This means that uncertainty of an SNQ should be taken into account when possible alternative reference spectra for calculation of R_{impact} or alternative reference curves will be developed. The measurement uncertainty at low frequency range, however, does not become so large that it would prevent developing new reference curves that weight this frequency range more strictly then the present, standardized reference curves starting at 100 Hz.

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